

UVB RADIATION

Definition and Characteristics

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Introduction

It could be simply stated that UVB radiation is that portion of the electromagnetic spectrum from 290-320 nanometers. This definition would be meaningful and sufficient for those who have an adequate science background. However, for many, this explanation will have little meaning. Therefore the following is designed to lead the reader through a discussion of solar radiation and

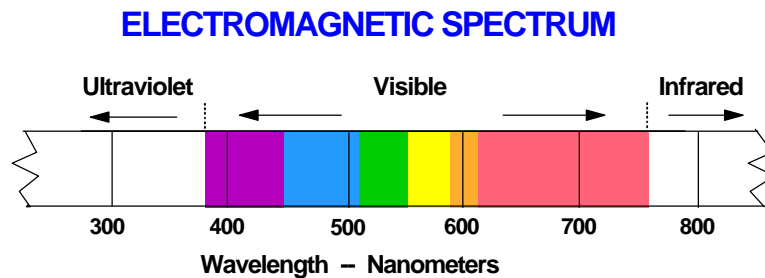


Figure 1 *Visible portion of solar radiation.*

its characteristics in order to better understand the relationship of UVB to that portion of the electromagnetic spectrum we refer to as “ultraviolet”, “visible” and “infrared” radiation (see Figure 1). Also discussed will be how ozone affects the UVB portion of solar radiation reaching the earth’s surface as well as the relationship of UVB to the sensitivity of biological organisms.

The Solar Radiation Spectrum

UVB radiation refers to a specific portion of the sun’s energy reaching the earth’s surface. To understand how this is defined, we need to understand the general nature of solar energy. The energy of the sun reaching the earth is known as electromagnetic radiation. If we were to observe the sun above the earth’s atmosphere, it would be found that the electromagnetic radiation consisted of the many forms of energy we recognize as visible light, infrared, ultraviolet, X-rays, etc. These terms simply define different those portions of electromagnetic radiation with which we associate specific phenomena such as sight (light), heat (infra-red), medical examinations (X-rays). They are all portions of the electromagnetic radiation that differ from one another in

“energy”. The more energetic regions of the spectrum are at smaller or shorter wavelengths. In the very limited portion of the total electromagnetic spectrum shown in the Figure 1, it is noted that ultraviolet is found at the short wavelength end (higher energy) and infrared at the long wavelength end (lower energy). At wavelengths longer than the infrared you will find microwaves and radio waves. At wavelengths much shorter than ultraviolet you will find X-rays and gamma rays. You will probably recognize that X-rays are very energetic since they can penetrate solid matter that visible light cannot penetrate and we thus cannot “see through”. Of critical importance to life on earth are the ultraviolet, visible and infrared spectral regions. For example, infrared and visible energy is that portion of the sun’s spectrum that is responsible for heating the earth.

Spectral Region	Wavelength	% of Total Energy
Infrared	>700 nm	49.4
Visible	400-700 nm	42.3
UVA	400-320 nm	6.3
UVB	320-290 nm	1.5
UVC	<290 nm	0.5

Table 1 Distribution of solar irradiance energy.

In discussing UV radiation, it should be noted that this represents a very small portion of the total radiation from the sun that reaches the earth’s surface. Much is filtered out by our atmosphere. Table 1 lists the various regions of the solar spectrum, indicating the percentage of total solar energy in each region. UV radiation (represented by UVA, UVB, and UVC which will be defined in a following section) makes up only a little over 8% of the total. Most of the solar radiation is in the visible and infrared.

Wavelength and Frequency

In order to discuss the characteristics of solar radiation, it is necessary to define the terminology used to describe the physical nature of electromagnetic radiation. Early scientists described electromagnetic radiation or “light” as having a “wave nature”. This explained the behavior of light as it was bent by a lens or dispersed into various colors (spectrum) by a prism or by water droplets forming a rainbow. Electromagnetic radiation can be represented as a continuous wave, a portion of which is shown in the Figure 2. The wavelength is defined as the

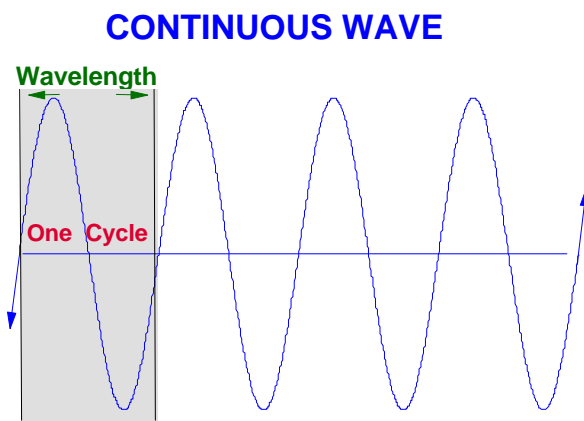


Figure 2 Sine wave showing definition of wavelength. length of one cycle (smallest segment that can be repeated to generate a continuous wave). For

visible light, wavelength is usually expressed in nanometers (nm) (1 nanometer = 10^{-9} centimeters) or Angstroms (1 Angstrom = 10^{-8} centimeters). Visible light ranges from 380 to 770 nanometers (nm) or 3,800 to 7,700 Angstroms (see Figure 1).

Another way of expressing the nature of electromagnetic radiation is as frequency which is defined as the number of cycles per second. For radio waves, frequency is the usual designation rather than wavelength. Since radiation travels at speed of light (approximately 3.0×10^{10} cm per second) and if we know the wavelength, the frequency in cycles (see cycle Figure 2) per second can be calculated by dividing speed of light by the wavelength. This is expressed by the equation below where ν is the frequency, c is the rate at which radiation travels (3.0×10^{10} centimeters per second) and λ is the wavelength in centimeters.

$$\nu = \frac{c}{\lambda}$$

Energy and Photons

Treating electromagnetic radiation as a wave, while explaining many of the phenomena associated with its behavior, is not satisfactory when describing many of its interaction with matter. It is necessary to describe it in terms of a particle called a “photon”. In other words, radiation has a dual nature - some phenomena related to its wave nature and other phenomena associated with its particle nature. It is the particle nature which we need to understand in order to explain the interactions of radiation with ozone and biological organisms which will be discussed later.

It is now necessary to define the energy of the photons occurring at various wavelengths or frequencies. An early German physicist, Max Planck, determined that the energy of radiation or photons at a given frequency was simply expressed as a constant times the frequency or:

$$E = h\nu = \frac{hc}{\lambda}$$

E is the energy expressed in units called “ergs” and h is Planck’s constant which is 6.63×10^{-27} erg sec.

From this expression it can be seen that as frequency increases and wavelength decreases the energy of the photons increase. For example, photons associated with ultraviolet radiation are more energetic than those associated with infrared radiation. Thus, short wavelength radiation is more energetic than long wavelength radiation.

Interactions of Radiation with Matter

We observe the interaction of matter and light all around us. The grass is green because “red and blue” photons are absorbed by the plants chlorophyll or a car is red because blue-green light is absorbed by the paint. Matter can also emit photons (as opposed to absorption) if it heated to high enough temperature or “excited”. The light from fluorescent lamps is a result of the excitation of mercury vapor by high energy electrons, which then emits photons (actually in the UV) which in turn interact with a “phosphor” coated on the tube walls to emit the bluish visible light. The yellowish street lamps are the result of photons emitted by hot or “excited” sodium vapor. Thus, the interaction between matter and electromagnetic radiation can result in either the absorption or emission of photons depending on the phenomena being observed.

In discussing the interactions of UVB radiation with biological organisms we are primarily concerned with the absorption phenomena. Keep in mind that the source of this radiation is the sun which is hot enough to emit photons with a wide range of energies. In this discussion, the concern is with the range of photon energies referred to as UV which, through absorption, can damage biological organisms. On the other hand, it should be kept in mind that the absorption of visible radiation by plants, particularly photons in the blue and red region (400-500 and 650-780 nm) is the source of energy driving photosynthesis. Since our interest is with UV radiation, the following discussions will focus on its ability to be absorbed by and break the bonds between atoms in molecules which, in the case of biological organisms, may result in permanent damage.

Ultraviolet Radiation Absorption

Up to now the discussion has been of electromagnetic radiation in general. The following will focus on that portion of the spectrum designated as UV radiation. In Figure 3 the UV portion of the spectrum is divided into UVA, UVB, and UVC. These designations are somewhat arbitrary, but they are convenient divisions for the discussion of the interaction of UV radiation with ozone and biological organisms.

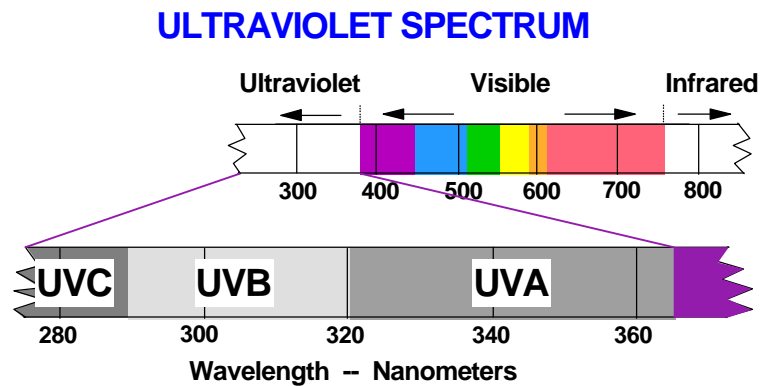


Figure 3 Diagram showing ultraviolet portion of solar spectrum.

The UVB and UVC radiation represents that portion of the spectrum that is capable of damaging biological organisms and is also that portion absorbed by the ozone layer above the earth. High energy UVC photons (wavelengths shorter than 290 nm) are almost completely absorbed by ozone and very few reach the earth's surface. This is fortunate since life as we know it would not exist if this were not the case. For example, UVC radiation is emitted from “germicidal” lamps which are used to kill

biological organisms. UVB radiation (wavelengths between 290 and 320 nm) is only partially absorbed by the ozone layer and can damage biological organisms while UVA (wavelengths greater than 320 nm) is not absorbed by ozone and generally is not damaging to biological organisms. These relationships will be discussed in more detail in a later section.

Intensity of Radiation

Another consideration in evaluating the effects of UV radiation is the intensity or “flux” at the earth’s surface. That is, how much radiation of a given wavelength is reaching the earth’s surface. You might think of flux in terms of a 20 watt light bulb and a 100 watt light bulb. Both emit roughly the same spectral range of wavelengths - both are “white” visible light. However, there is a large difference in intensity and thus in the amount of light or radiation “flux”. The term used to define the flux of solar radiation is “irradiance”. The solar irradiance at the earth’s surface varies greatly depending on factors such as latitude, time of day, time of year, cloud cover, and haze (aerosols). In the case of the UV irradiance, additional factors are ozone and elevation above sea level.

The units in which irradiance is expressed are watts per meter squared - the amount of light falling on a horizontal square meter of surface and measured in watts. If the radiation is separated into its spectrum, the irradiance at a specific wavelength can be expressed as watts per meter squared per nanometer of wavelength. It should be obvious that in the interaction of radiant energy with biological organisms, we have to consider both wavelength and irradiance. For example, in the case of photosynthesis an increasing irradiance in the visible may increase the photo synthetic rate depending on the plant. Thus when discussing the potential negative effects of UVB radiation on biological organisms, not only is the wavelength and energy of the photons important but also the radiation flux or irradiance levels.

Ozone Control of UVB Irradiance

As previously stated, the protection of the earth’s living systems from UVB and UVC radiation is a result of the absorption of this radiation by ozone. While there is some ozone in the lower atmosphere (troposphere), it is small compared to the amount in the stratosphere. (It is not the purpose of this presentation to discuss the chemistry which has resulted in reductions of stratospheric ozone but to describe how changes in the ozone layer can effect the UV irradiance). The most important factor is the total amount of ozone that solar radiation encounters before reaching the earth’s surface. This is referred to as “column ozone” since it is the total amount of ozone in a column between the earth’s surface and the top of the stratosphere. This is normally expressed as “Dobson Units” and abbreviated as “DU”.

SOLAR ZENITH ANGLE - SZA

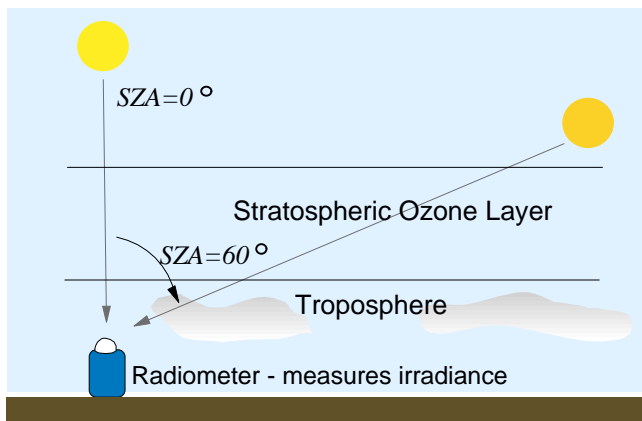


Figure 4 Path length through atmosphere and SZA

on three factors - the latitude, the time of year, and the time of day. This angle is referred to as the “solar zenith angle” (SZA) and is the angular difference in degrees between directly overhead and the sun’s actual position. If the sun were directly overhead the SZA would be zero. This can occur only at latitudes between 23.5° north and 23.5° south. Thus, in the northern and southern latitudes greater than 23.5°, the sun never reaches a SZA of zero degrees.

The amount of ozone the radiation passes through is dependent not only on its concentration in the atmosphere but is also dependent on the elevation above sea level and the angle of the sun with respect to a point on the earth’s surface. The higher the elevation above sea level, the shorter the path through the atmosphere that the radiation has to travel. This results in increasing irradiance. The lower the sun is in the sky, the longer the path through the atmosphere (see Figure 4) and the greater the amount of ozone the radiation encounters as it passes to the earth’s surface thus lowering the irradiance. The angle of the sun depends

IRRADIANCE

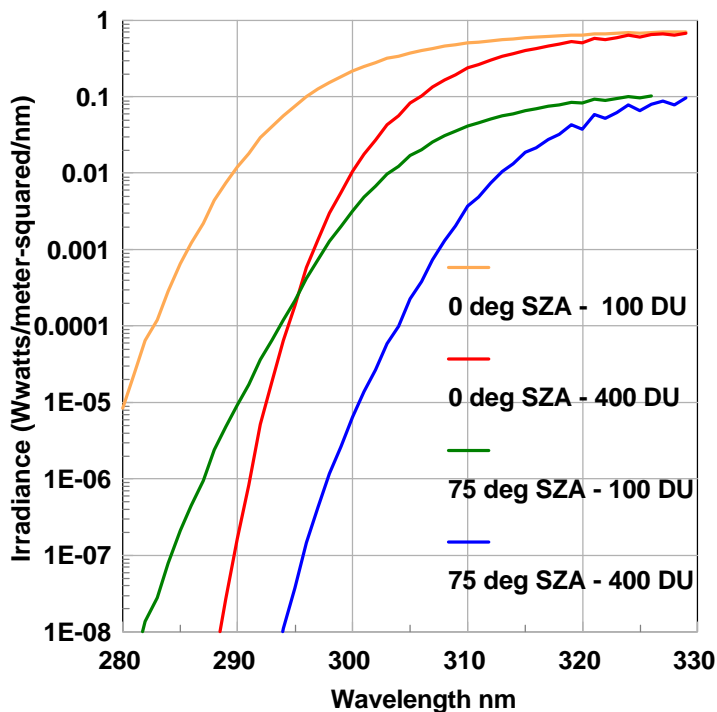


Figure 5 Effect of sun’s angle and ozone on irradiance.

In order understand the relationship between the amount of solar UV reaching the earth it is necessary to account for both the SZA and column ozone. This relationship is displayed in the graphs in Figure 5. For illustration, solar irradiance is plotted (logarithmic scale) versus wavelength at column ozone amounts of 100 DU and 400 DU (normal levels for the U. S. latitudes are 260-350 DU) and SZAs of 0° and 75° on a clear day (role of clouds will be considered later). The sun angle of 0° could represent a location at 23.5° north latitude (for example La Paz, Mexico) at

solar noon on the 21st of June (day sun is farthest north). The sun angle of 75° could represent approximately 6:00 AM or 6:00 PM on the same day. There are obviously many combinations of time of day, day of the year and geographical locations (between 23.5° south and 23.5° north) which would produce these conditions. If farther north or farther south than 23.5°, the sun will never be overhead or at 0° SZA.

From Figure 5 it can be seen that the irradiance varies strongly with wavelength and at 400 DU and at 0° sun angle, the irradiance at 290 nm is only one-one hundred millionth of that at 320 nm. This illustrates the important role ozone plays in filtering out radiation at wavelengths shorter than 320 nm. As the solar angle increases to 75° late in the day, the path through the atmosphere has increased and the irradiance has decreased significantly as a result of increased ozone absorption as well the fact the sun is at a more oblique angle with respect to the earth's surface. If the column ozone were reduced from 400 DU to 100 DU it is obvious that there is a large effect on UV absorption. At a solar angle of 0° the absorption at 290 nm has increased by a factor of one hundred thousand. (A column ozone value of 100 DU in the northern and southern mid-latitudes is entirely unrealistic and was chosen for illustration purposes only). A value as low as 100 DU has occurred over the antarctic continent as a result of the "ozone hole" but the SZA is never less than 55 degrees at this latitude.

Interesting, and little noticed, are the implications of SZA and latitude for UVB irradiance. Where you live has a large effect on the UVB dose you may receive for a given exposure time. To illustrate this, if you live in Las Cruces, NM at 32.6° north latitude, on June 21st on a clear day with an ozone level of 300 DU, you would receive a UVB dose 1.24 times that which you would receive in Seattle, WA at 47.7° north under the same atmospheric conditions. This would be equivalent to increasing the ozone levels by about 50 DU to 350 DU at Las Cruces. This results from the fact that the sun does not rise as high in the sky as you move farther north.

Clouds, Aerosols, and Air Pollution

It should come as no surprise that clouds have a large effect on irradiance at the earth's surface. Clouds and aerosols scatter radiation while air pollutants such as sulfur dioxide absorb and scatter UV. Absorption of UV by gasses other than ozone is generally a small factor except in highly polluted areas. The illustration in Figure 6 depicts the three

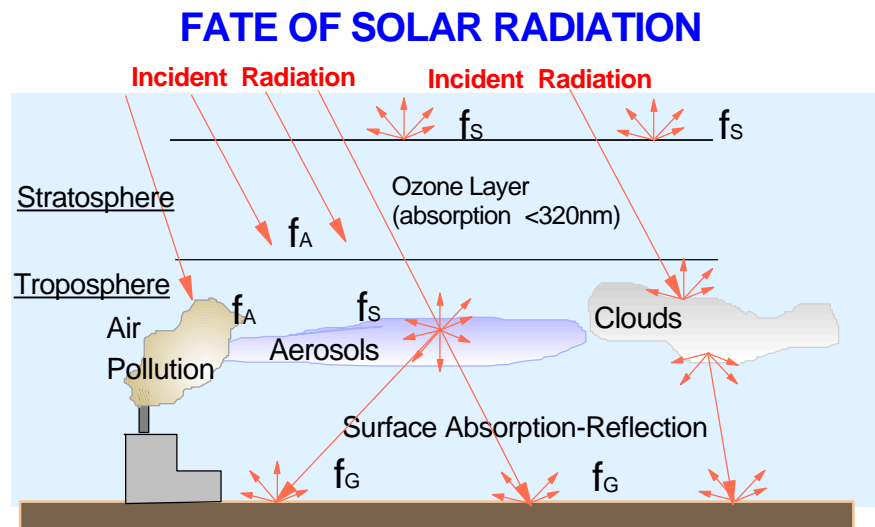


Figure 6 Interaction of radiation and the earth's atmosphere.

factors which effect the transmission of solar radiation to the earth's surface. These are absorption in the atmosphere (f_A) by ozone and air pollutants, scattering back to space (f_S) by molecules, clouds and aerosols (haze), and absorption by the ground (f_G). If the ground is covered by snow or ice, absorption is low. The reflectivity of the ground is expressed as the "albedo". The albedo of clean snow is almost one (100% reflection) reflecting a large portion of the radiation. For example, the reflective nature of snow greatly increases the exposure of a skier to UVB thus increasing the severity of sunburn and possibly resulting in "snow blindness" if not wearing goggles. Blacktop, on the other hand, would have an albedo approaching zero. The sum of absorption and scattering ($f_A + f_S + f_G$) is equivalent to the total radiation entering the atmosphere.

To illustrate these effects (primarily for clouds), the plots in Figure 7 are actual field measurements of UV irradiance at 305 nm on a clear day and cloudy day in Texas on March 28 (clear) and 30 (cloudy). While there is cloud cover the entire day on the 30th, the UVB irradiance is still significant. As is illustrated in the previous figure, thin clouds actually scatter a significant portion of the UVB toward the earth while thick clouds scatter most back to space. Thus, clouds are not necessarily good protection from sun-burn.

IRRADIANCE - 305 NM

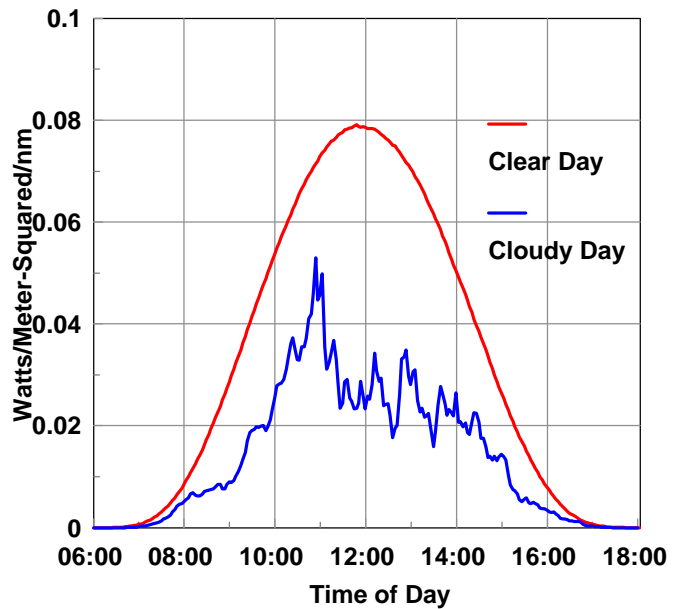


Figure 7 Irradiance for a clear and cloudy day.

Response of Biological Organism

The last step in our discussion is the relationship of UV radiation to biological organisms. Again, it is necessary to look at the nature of this interaction in terms of its dependence on wavelength. As stated previously, photons of sufficiently high energy can break the bonds between atoms in molecules and thus destroy the molecule. The higher the energy of the photon, the more likely that the interaction will be destructive. Also, the larger the number of photons or the higher the irradiance, the greater the damage. We saw in the previous section that as the wavelength decreases, the photons have higher energy but there are fewer of them because of the absorption by ozone (red curve in Figure 8). On the other hand, the sensitivity of biological organisms increases as the wavelength becomes shorter (green curve Figure 8) because of the higher photon energy. Thus, there will be some wavelength which causes the greatest damage based on organism sensitivity and irradiance level. We can determine the most destructive wavelengths if we can experimentally determine the amount of damage to a given organism as a function of wavelength or photon energy. Such a function is called an "action spectra" and is specific for a given organism. If action spectra are compared for a variety of biological organisms, while they will all be different, there is not a great deal of variation.

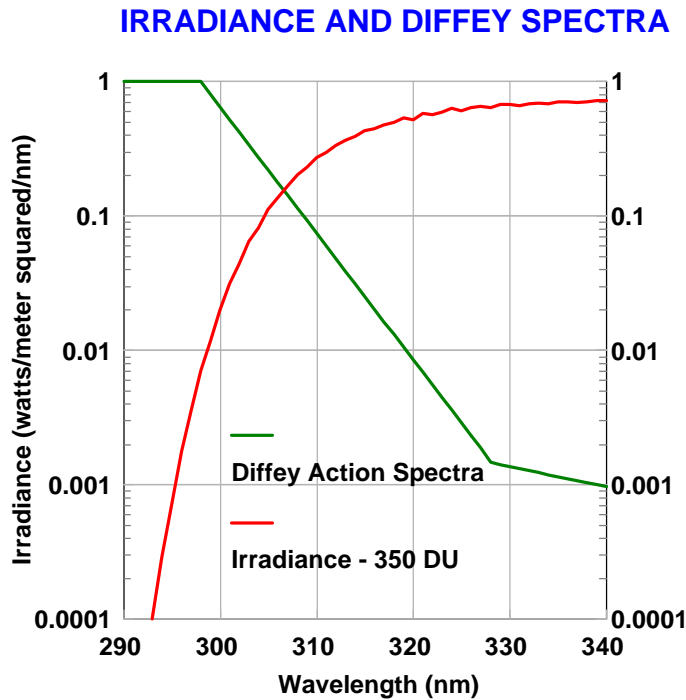


Figure 8 Modeled irradiance (350 DU and 0 SZA) and Diffey action spectra.

logarithmically as a result of ozone absorption. In order to determine the wavelengths where greatest damage occurs, we simply multiply the two functions together (the values in the Diffey curve times those in the irradiance curve). The result is shown in Figure 9. This process is called “weighting”. We see that the most destructive wavelengths are around 305 nm. At shorter wavelengths, there are not enough photons and at longer wavelengths, the photon energy is not high enough to cause as much damage. It turns out that for most biological organisms the most destructive wavelengths are between 305 and 310 nm.

Summary

We have seen that electromagnetic radiation spans wavelengths from long wavelength radio waves to short wavelength X-rays and gamma rays. Wavelength can be converted to frequency by dividing the speed of light by wavelength. Classical physics treats electromagnetic radiation as a wave while the particle nature of radiation is invoked to describe its absorption by matter. In this case, radiation is described in terms of

For purposes of this discussion, the action or damage spectra for sun-burn was chosen (Diffey action spectra). This is plotted as a function of wavelength (green curve) on the graph in Figure 8 and represents the relative response of human skin to UVB as a function of wavelength (action spectra are expressed in relative units - one representing the highest sensitivity). To determine the skin’s response, the number of photons to which the skin is exposed is essentially the same at each wavelength. You will note that as the wavelength is decreased, the damage increases logarithmically (changing by factors of ten) and that the sensitivity of skin at 290 nm is a thousand times that at 340 nm. At the same time, the sun’s irradiance or number of photons (red curve) is decreasing

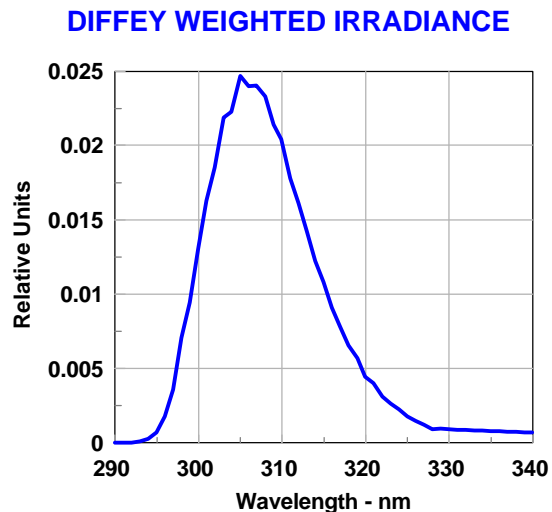


Figure 9 Product of the irradiance and Diffey action spectra as shown in Figure 7.

photons which have an energy $E=h\nu$. This relation demonstrates that photon energy increases with increasing frequency and decreasing wavelength. Photons, depending on their energy, are capable of being absorbed by biological molecules and, at wavelengths shorter than 320 nm, breaking molecular bonds and causing damage which may be irreparable. On the other hand, at energies greater than 320 nm, ozone is absorbing the UVB and UVC radiation and greatly reducing the number or flux of these high energy photons reaching the earth's surface.

In an earlier section it was noted that ozone may drop to 100 DU in the antarctic during the ozone hole but at that latitude the solar angle is never less than 55° . Because of the low sun angle, the UV irradiance generally does not exceed normal values at mid-latitudes. It should be pointed out, however, that this does represent abnormally high UVB irradiance for the plants and animals that have evolved in this region of the world and in fact does represent a problem. There are demonstrated harmful effects of increased UVB radiation on aquatic organisms in the antarctic, particularly phytoplankton which is a critical component of the food chain. Skin cancer, increased incidence of cataracts, DNA damage, the negative response of phytoplankton and other plants are all related to elevated UVB. *These represent only a few of the negative effects observed as a result of UVB absorption by biological and geochemical systems which clearly illustrate the importance of maintaining normal ozone levels in the stratosphere thus increasing the absorption of the short wavelength UV radiation.*

SITES WITH UVB RADIATION RELATED INFORMATION

For more information on the measurement and magnitude of UVB radiation in the United States.

! <http://uvb.nrel.colostate.edu/>

For additional information on the response of biological organisms to UVB radiation.

! <http://www.ciesin.org/TG/OZ/oz-home.html>