TOPIC 1. RADIANT ENERGY

The relationship between the sun and the earth provides the basic framework for atmospheric physics and biological productivity. The sun's energy generates thermal gradients in the atmosphere that result in temperature differences, density and pressure differences, and liquid-vapor changes in surface and atmospheric water. The sun's energy is also used by plants to synthesize new compounds by the process of photosynthesis, resulting in primary production.

There are two concurrent periodic rhythms--daily and yearly--in the duration and amount of solar energy received at the earth's surface, with the length of each related to the day of the year and the location on the earth. The transitions from one phase to another in both of these rhythms are gradual. Daylength reaches a maximum at the summer solstice and a minimum at the winter solstice. Sunlight intensity reaches a maximum at solar noon and goes to zero at night. Changes in the earth-atmosphere energy balance are gradual as a result of these changes in day length and sunlight intensity.

The sun continuously emits radiation into space as a result of the conversion of mass into energy. While the sun's mass is slowly being converted to energy as it radiates into space, the actual mass of the sun is so large that after a billion years of mass-to-energy conversions, 99.99% of the sun's mass remains! (See Miller 1972; p. 152).

Radiant energy may be visualized as a collection of waves that can be described by their wavelengths, or distances from peak to peak as illustrated above. The sun emits a wide range of wavelengths, including very short ones called X-rays, with wavelengths of a few microns, and very long ones, called radio waves, with wavelengths of many kilometers. The wavelengths of maximum emission (WLME) from the sun falls within the range of the visible spectrum, or those wavelengths which we humans are capable of detecting as visible light. The micron and the Angstrom are two units of measurement commonly applied to wavelengths in the visible and infrared portion of the electromagnetic spectrum. The micron is one millionth of a meter, one-ten thousandths of a centimeter (1 x 10^-6 cm), or one thousandth of a millimeter. The Angstrom is 1/1000 of a micron.
The electromagnetic spectrum includes wavelengths as long as hundreds of kilometers and as short as 1 x 10^{-10} cm (0.0000000001 cm). The categories of wavelengths between these two extremes are listed below.

<table>
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<tr>
<th>Kind of Waves</th>
<th>Approximate Wave Length Range --Metric Units</th>
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<tr>
<td>Long Electromagnetic Waves</td>
<td>Hundreds of kilometers to 17 kilometers</td>
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<td>Assigned Radio Range</td>
<td>17 kilometers to 75 centimeters</td>
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<td>Ultra-short Radio Waves</td>
<td>75 cm to .025 cm</td>
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<tr>
<td>Infra-red or Heat Rays</td>
<td>2.5 x 10^{-2} to 7.0 x 10^{-5}</td>
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<td>Visible Light</td>
<td>7.0 x 10^{-5} x to 3.5 x 10^{-5}</td>
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<td>Ultra-violet Rays</td>
<td>3.5 x 10^{-5} to 1.3 x 10^{-6}</td>
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<tr>
<td>X-rays</td>
<td>1.3 x 10^{-6} to 1.0 x 10^{-9}</td>
</tr>
<tr>
<td>Gamma Rays</td>
<td>1.0 x 10^{-9} to 1.0 x 1.0^{-10}</td>
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</table>

The part of the electromagnetic spectrum of importance to free-ranging animals, especially in the maintenance of homeothermy, includes the wavelengths in the visible to the far infrared portion of the electromagnetic spectrum.

Every surface which has a temperature higher than absolute zero emits radiant energy. The wavelengths emitted are proportional to the fourth power of the absolute temperature (K) of the radiating surface. High-temperature surfaces, such as the sun (60000K) emit mainly at shorter wavelengths, and cooler surfaces, such as the earth's surface (3000K), emit the longer, or infrared wavelengths.

The wavelength of maximum emission is related to the temperature of the radiating surface according to Wien's Displacement Law, which may be expressed as:

\[
\text{WLME} = \frac{c}{ERTK}
\]

where \( c = 0.2898 \text{ cm °K} \) (Rosenberg 1974: 8), and

\( ERTK = \text{effective radiant temperature in °K.} \)

WLME for the sun is, then:

\[
\text{WLME} = \frac{0.2898}{6000} = 4.83 \times 10^{-5}
\]
This wavelength, \(4.83 \times 10^{-5}\), is within the visible part of the electromagnetic spectrum. \(W_L^T\) for a plant or an animal with a radiant temperature of 27°C, or 300 K, typical of a warm summer day, is:

\[
W_L^T = \frac{0.2898}{300} = 9.66 \times 10^{-4}\ \text{cm}
\]

This wavelength, which is within the far infrared portion of the electromagnetic spectrum, is detected only as heat energy by animals.

The temperature: wavelength relationship is experienced when watching a campfire burn to a bed of hot, bright red coals. As the coals cool down, they become a deeper and deeper red until they no longer glow. They have passed from a light- and heat-emitting temperature range to a heat-emitting temperature range only, and the wavelengths have become longer as the temperature has decreased. The wavelengths have shifted from the visible to the near infrared to the far infrared portion of the electromagnetic spectrum.

The amount of radiation received by a surface is inversely proportional to the square of the distance between the source and the receiving surface. This relationship is illustrated below.

![Diagram](source.jpg)

If the distance is doubled (2d:1d), the radiant energy covers 4 times the area (4a:1a). If d = 4, then a = 16. It is easy to see that the radiant energy from one square cm of the sun's surface is very much spread out by the time it reaches the earth 93,000,000 miles away.

The basic relationships discussed above apply to both the solar and infrared radiation that are a part of the thermal environment of plants and animals. Solar energy is discussed in UNIT 1.1, and infrared energy in UNIT 1.2.

**LITERATURE CITED**


UNIT 1.1: SOLAR ENERGY

Solar energy flux in the biosphere is a fundamental, driving force for ecological processes. It is the source of power driving the physical processes of the biosphere—wind, rain, weather systems, erosive actions—and the source of power driving biological processes—photosynthesis (directly) and respiration (indirectly)—in the ecological matrix within this physical superstructure.

Differences in solar energy distribution over the surface of the earth result in marked differences in plant communities. The curved surface of the earth contributes to several physical gradients; the polar regions receive different amounts of solar energy than the equatorial regions, and the light rays strike the earth at much different angles through the annual cycle at the poles than at the equator. The timing and distribution of radiant energy exchange follows some rather strict natural laws, and the ecological effects are predictable.

The amount of energy intercepted by a one-square centimeter surface at right angles to the solar beam on the outer limit of the earth's atmosphere is called the solar constant. It is the upper limit to the amount of energy reaching the earth, yet it is only $1.8999 \times 10^{-5}$ or 0.000018999 of the energy given off by a square cm of the sun's surface! This very small fraction is due to the distance effects described by the inverse square law. The numerical value of the solar constant was measured by Johnson in 1954 to be 2.00 cal cm$^{-2}$ min$^{-1}$ (139.5 mw cm$^{-2}$), and this was considered the most authoritative until Thekaekara and Drummond (1971) proposed a standard value of 1.94 cal cm$^{-2}$ min$^{-1}$ (135.3 $\pm$ 2.0 mw cm$^{-2}$) (See Paltridge and Platt 1976: 53). Not all of the sun's energy reaches the surface of the earth. Some of it is reflected into space by dust particles and clouds in the atmosphere. On a clear day, a high percentage of the solar radiation is transmitted through the atmosphere. With a completely overcast sky, no direct solar radiation penetrates the cloud cover, and ultraviolet radiation penetrates more than the longer wave lengths. The actual amount received at the earth's surface is less than the solar constant because of reflection and absorption by the atmosphere.

A unit area of the earth's surface does not receive a constant amount of radiant energy. Everyone is familiar with the daily and seasonal patterns of sunrise and sunset times; longer days in the summer and shorter days in the winter are characteristic of both hemispheres. The sun's pathway is lower in the sky in the winter and the arc is shorter. At the poles, the sun does not appear above the horizon in the winter, and it does not go below the horizon in the summer. The patterns of the sun's apparent movements are reversed between the northern and southern hemispheres, of course; summer occurs in only one hemisphere at a time.
The apparent movements of the sun are illustrated in the drawing below.

Solar energy flux on a clear day increases from sunrise to solar noon and decreases from solar noon to sunset. The pattern is nearly symmetrical about solar noon for a horizontal plane at the earth's surface, as illustrated by the tracing of two daily pyranometer recordings below.

Measured amounts of solar energy reaching the earth's surface are dependent on the sun's angle, atmospheric conditions, and altitude above sea level. The average solar radiation reaching a horizontal surface in the northern states in January is 125-150 cal cm$^{-2}$ day$^{-1}$, and in July, 500-650 cal cm$^{-2}$ day$^{-1}$ (See Moen 1973 or Sellers 1965). Measurements can be expressed mathematically through the annual cycle; the WORKSHEETS that follow provide opportunities for calculating solar energy.


### REFERENCES, UNIT 1.1

### SOLAR ENERGY

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CJBOA 44-10 1267 1284 ---- spec comp, uv, visual radi vezina,pe; boulte 1966
CJTEA 33... 12 32 ---- insola cloudls days, canad mateer,cl 1955
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FOSCA 7---2 144 145 ---- var, meas ligh intensity, for gatherum, ge 1961
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CHAPTER 14, WORKSHEET 1.1a

Calculations of daily solar energy over the annual cycle

Very simple first approximations of the daily solar energy reaching a horizontal surface over the annual cycle may be made with a sine wave calculation. Suppose that 150 calories per square centimeter per day (CSCD) reached this surface at the time of the winter solstice (December 21 = JDAY 355) and 650 CSCD at the time of the summer solstice (June 21 = JDAY 172). The midpoint radiation (MPRA) is then 400 CSCD. The daily solar radiation (SORA) can be calculated with these facts and a primary phase correction arranged according to the following formula:

\[ \text{SORA} = \text{MPRA} + \sin[(\text{JDAY})(0.9863) + \text{PRPC}] \times \text{AMPL} \]

where SORA = solar radiation  
MPRA = midpoint radiation value  
PRPC = primary phase correction  
AMPL = amplitude of the variation from MPRA

Determine the primary phase correction, PRPC, by:

\[ \sin[(\text{JDMA})(0.9863) + \text{PRPC}] = 1.0 \]

where JDMA = JDAY at maximum.

Since \( \sin 90 = 1.0 \),

\[ [(\text{JDMA})(0.9863) + \text{PRPC}] = 90 \]

\[ 90 - (\ldots)(0.9863) = \ldots = \text{PRPC} \]

MPRA in this example is 400 and AMPL = 250. The equation is:

\[ \text{SORA} = 400 + \sin[(\text{JDAY})(0.9863) + \text{PRPC}] \times 250 \]

Calculate SORA at 20-day intervals and plot the curve.
UNIT 1.2: INFRARED RADIATION

Radiation of wavelengths longer than those in the visible portion of the spectrum is called infrared or thermal radiation.

The earth and its atmosphere are an infrared radiating surface in the emptiness of space. The earth continuously radiates infrared energy and emits as much radiant energy as it absorbs. If it emitted less, it would become warmer, and if it emitted more, cooler.

Little attention has been given to thermal radiation by ecologists, and this is probably due in part to the invisible characteristic of infrared radiation. The wavelengths are not detected by the human eyes, so it has often been overlooked as a part of the entire thermal regime. An object is seen because of visible reflected light but its longer wavelengths are detected only as heat energy.

The amount of thermal energy radiation from any surface is proportional to the fourth power of the absolute temperature of the radiating surface, according to the Stefan-Boltzmann law. The formula is:

\[ Q_{\text{REE}} = (SBCO)(ERTK)^4 \]

where \( Q_{\text{REE}} \) = quantity of radiation emitted,
\( SBCO \) = Stefan-Boltzmann constant, and
\( ERTK \) = effective radiant temperature in °K.

The radiation emitted from a surface with a radiant temperature of 27 °C or 300 K can be calculated with the equation:

\[ Q_{\text{REE}} = (8.127 \times 10^{-11})(300^4) = 0.658 \text{ cal cm}^{-2}\text{min}^{-1} \]

Another factor, infrared emissivity (IREM), may be added to the formula above. The numerical value for IREM is equal to the infrared absorption coefficient. The absorption coefficient is the ratio of absorption by a surface to that of a black body, or perfect absorber. Thus if a surface absorbs 85% of the radiant energy that reaches it, the absorption coefficient is 0.85. The formula for calculating radiant energy as a function of both emissivity and temperature is:

\[ Q_r = (IREM)(SBCO)(ERTK)^4 \]

It is useful to prepare a nomogram of infrared energy emitted for use in thermal exchange estimations. Calculations with the above formula have been made and the family of curves for emissivities ranging from 1.0 to 0.08 plotted in the nomogram on the next page.
The relationships between environmental radiant temperature (Celsius) and quantity of radiant energy emitted (QREE) in kcal m⁻²hr⁻¹ (KMTH) for different infrared emissivities (IREM) is illustrated below.

ERTC = -40 -30 -20 -10 0 +10 +20 +30 +40
ERTK = 233 243 253 263 273 283 293 303 313
REFERENCES, UNIT 1.2

INFRARED RADIATION

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CHAPTER 14, WORKSHEET 1.2a

Infrared radiation in relation to radiant surface temperature

The formula for calculating the quantity of radiant energy emitted (QREE) from a surface is:

\[ Q_{REE} = (SBCO)(ERTK)^4 \]

where ERTK = effective radiant temperature in degrees Kelvin, and SBCO = Stefan-Boltzmann constant.

When QREE is in calories per square cm per minute (CPCM), then \( SBCO = 8.127 \times 10^{-11} \), and when QREE is in kilocalories per square meter per hour (KMTH), then \( SBCO = 4.876 \times 10^{-8} \) (See Moen 1973:429).

Equivalent temperatures in Celsius and Kelvin degrees are:

\[
\begin{align*}
-40 \degree C &= 233.16 \degree K \\
-30 &= 243.16 \\
-20 &= 253.16 \\
-10 &= 263.16 \\
0 &= 273.16 \\
+10 &= 283.16 \\
+20 &= 293.16 \\
+30 &= 303.16 \\
+40 &= 313.16
\end{align*}
\]

Substitute these temperatures in the formula above and plot the results below. Note that QREE is in CPCM on the left-hand scale, and KMTH on the right-hand scale. Compare your values to the IREM = 1.0 line in the nomogram.