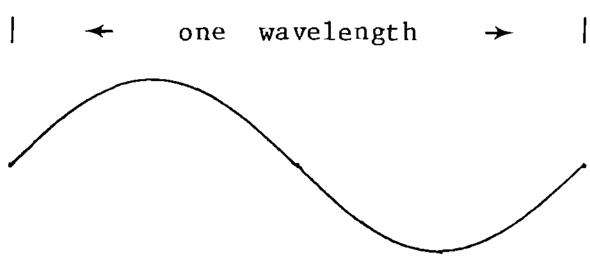
TOPIC 1. RADIANT ENERGY

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 illu-



strated 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 (1×10^{-4}cm), or one thousandth of a millimeter. The Angstrom is 1/1000 of a micron.

The electromagnetic spectrum includes wave lengths 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.

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

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

```
                                            NEAR IR
      XRAY      ULTRAVIOLET VISIBLE    INTERMEDIATE IR      FAR  INFRARED
|........|..............|.....|....|............|.......................|
|          |            |          |            |            |          |
10A       100A        1000A       1um         10um        100um     1000um
```

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 (6000°K) emit mainly at shorter wavelengths, and cooler surfaces, such as the earth's surface (300°K), 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:

$$WLME = c/ERTK$$

where c = 0.2898 cm °K (Rosenberg 1974: 8), and
ERTK = effective radiant temperature in °K.

WLME for the sun is, then:

$$WLME = 0.2898/6000 = 4.83 \times 10^{-5}$$

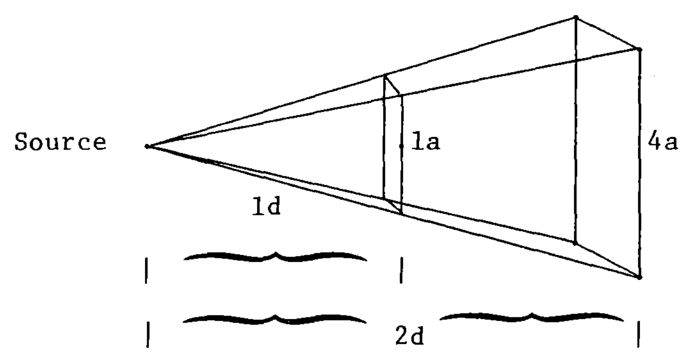
This wavelength, 4.83×10^{-5}, is within the visible part of the electromagnetic spectrum. WLME for a plant or an animal with a radiant temperature of 27 C, or 300 K, typical of a warm summer day, is:

$$WLME = 0.2898/300 = 9.66 \times 10^{-4} \text{ cm}$$

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.



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

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Rosenberg, N. J. 1974. Microclimate: The Biological Environment. John Wiley & Sons, N.Y. 315 p.

UNIT 1.1: SOLAR ENERGY

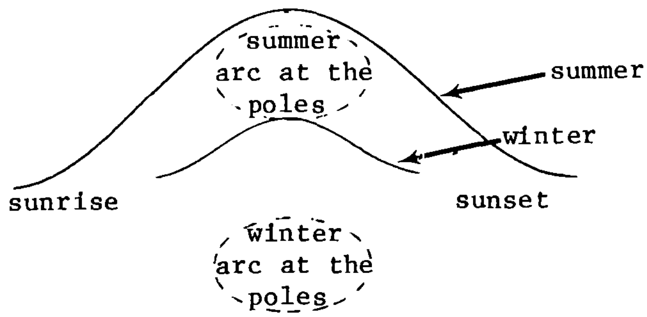
Solar energy flux in the biosphere is a fundamental, driving force for ecological processes. It is the source of power driving the physical processes of the biosphere--wind, rain, weather systems, erosive actions--and the source of power driving biological processes--photosynthesis (directly) and respiration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

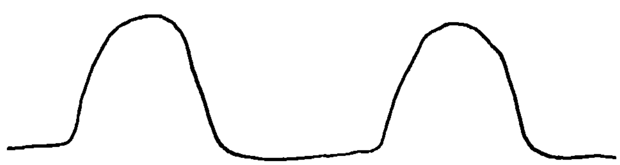
The amount of energy intercepted by a one-square centimeter surface at right angles to the solar beam on the outer limit of the earth's atmosphere is called the solar constant. It is the upper limit to the amount of energy reaching the earth, yet it is only 1.8999×10^{-5} or 0.000018999 of the energy 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 ± 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.

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Sellers, W. D. 1965. Physical Climatology. University of Chicago Press, Chicago. 272 p.

Thekaekera, M. P. and A. J. Drummond. 1971. Standard values for the solar constant and its spectral components. Nature (London), Phys. Sci. 229:6-9.

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SOLAR ENERGY

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TYPE	PUBL	CITY	PGES	ANIM	KEY WORDS-----------------	AUTHORS/EDITORS--	YEAR
aubo	haro	nyny	151	----	energy exchge in biosphere	gates,dm	1962
edbo	else	nyny	347	----	solar radiation	robinson,n	1966

SERIALS

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
AGMYA	1---1	54	65	----	sol rad ov sno pack, pine	vezina,pe	1964
AGMYA	7---1	19	28	----	interprt frctn, solr radtn	anderson,mc	1970
AGMYA	9-1/2	3	20	----	sol rad absrb, leaflss for	federer,ca	1972
AJBOA	38--5	327	331	----	refl vis infra rad, leaves	billings,wd; morr	1951
ANBOA	34---	329	348	----	penet rad, can, diff struc	newton,je; blackm	1970
ANSFA	28--4	425	442	----	hemisphr photos, lght clim	becker,m	1971
BOZHA	51--5	681	686	----	meth,light regimes, forest	akulova,ea/	1966
CJASA	35--6	579	594	----	est avrg insolatn in canad	mateer,cl	1955

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
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
CSTNA	12--3	63	74	----	light intensty study, w va	allard,ha	1932
ECOLA	4....	189	195	----	meas solar rad,plnt habita	burns,gp	1923
ECOLA	50--5	878	885	----	test models, 3 forst canap	miller,pc	1967
ECOLA	52--6	1008	1015	----	comp clear day sol ra spec	mccullough, ec; p	1971
EMFRA	37--2	222	232	----	light in the forest	brown,gs	1958
FIRAD	11--5	818	823	----	light transmiss, for canop	akulova,ea;/	1964
FOSCA	7---2	144	145	----	var, meas lght intens, for	gatherum,ge	1961
FOSCA	7---3	257	264	----	varia sol ra norway spruce	vezina,pe	1961
FOSCA	10--4	443	451	----	sol rad relat conif canopy	vezina,pe; pech,g	1964
FOSCA	12--3	258	267	----	top, insol clim, mou fores	lee,r; baumgartne	1966
FOSCA	16--2	a139	145	----	radiant energ, clrcut, for	hornbeck,jw	1970
FOSCA	18--4	273	277	----	eff clrcuttng, net radiatn	brown,jm	1972
FRSTA	28--2	141	146	----	compar light diff woodland	ovington,sd; madg	1955
FRSTA	31...	147	162	----	lght intnsty meas,for stnd	conner,rd; fairba	1958
HYSBA	9---1	27	41	----	pot insol, topoclim, drain	lee,r	1964
IJBMA	16--1	25	43	----	potntl solr rad,plnt shape	terjungl,wh; loui	1972
JAPEA	9---2	359	375	----	radtn, conif, decid forest	tajchman,sj	1972
JAPEA	10--2	657	660	----	flux vis, net rad, for can	kinerson,rs	1973
JECOA	44...	391	428	----	wdlnd lght intens,sunflcks	evans,gg	1956
JECOA	52...	27	41	----	photgrph comput, lght cond	anderson,mc	1964
JGREA	64-10	1617	1619	----	var,net exch of rad fr veg	decker,wl	1959
JGREA	67-13	5179	5185	----	energ bal, evap surf, arid	fritschen,lj; van	1962
JVAHA	20...	223	234	doca	absptvty solr rad, coats	riemerschmid,g; e	1945
LESOA	2----	31	37	----	rad regime, birch, spruce	molchanov,ag	1971
MMONA	4--23	1	43	----	atmospheric radiati tables	elsasser,wm; culb	1960
MWREA	63...	1	4	----	varia, intens solr radiatn	kimball,hh	1935
PSAFA	1964-	105	109	----	partition rad heat, forest	knoerr,kr	1964
SCIEA	164--	308	309	----	rad profl, canop, asp, oak	miller,pc	1969
SIFEA	113..	1	17	----	heat balance of the forest	dzerdzeevskii,bl	1963

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS----------------	AUTHORS----------	YEAR
XANEA	84---	1	21	----	radia measu, open, forests	lull,hw; reigner,	1967
XATBA	1344	1	111	----	rad energy relation to for	reifsnyder,we; lu	1965
XFRMA	18---	1	116	----	pot sol rad on slop, table	frank, ec; lee,r	1966
XFTBA	1344-	1	111	----	radnt enrg in reln forests	reifsnyder,we; lu	1965
XIPPA	269..	----	----	----	energy budget studies	anderson,er	1954

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Fons, W. L., H. D. Bruce, and A. McMasters. 1960. Tables for Estimating Direct Beam Solar Irradiation on Slopes at 30° to 46° Latitude. Pac. S.W. Forest and Range Expt. Sta., Berkeley, CA. 298 p.

Nagy, L. 1970 Data on radiation conditions in forests. Acta Climatologica 9(1.4):49-58.

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:

$$SORA = MPRA + \sin[(JDAY)(0.9863) + (PRPC)]\ [AMPL]$$

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:

$$\sin[(JDMA)(0.9863) + PRPC] = 1.0$$

where JDMA = JDAY at maximum.

Since sin 90 = 1.0,

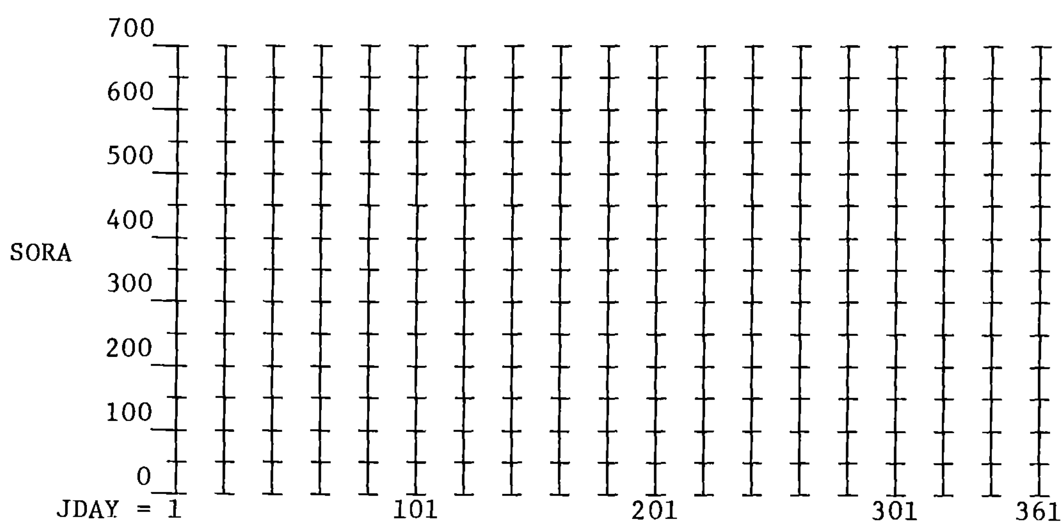
$$[(JDMA)(0.9863) + PRPC] = 90$$

$$90 - (\_\_\_\_)(0.9863) = \_\_\_\_ = PRPC$$

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

$$SORA = 400 + \sin[(JDAY)(0.9863) + (PRPC)]250$$

Calculate SORA at 20-day intervals and plot the curve.



UNIT 1.2: INFRARED RADIATION

Radiation of wave lengths 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:

$$QREE = (SBCO)(ERTK)^4$$

where QREE = quantity of radiation emitted,
SBCO = Stefan-Boltsmann constant, and
ERTK = effective radiant temperature in ^{o}K.

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

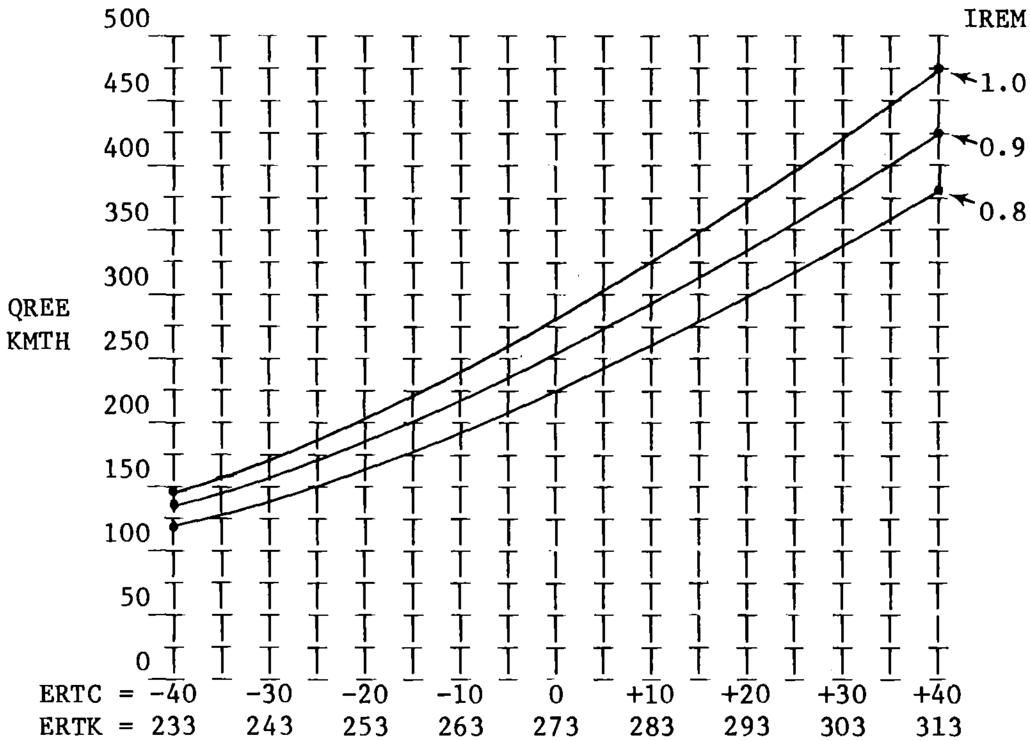
$$QREE = (8.127 \times 10^{-11})(300^4) = 0.658 \text{ cal cm}^{-2}\text{min}^{-1}$$

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 $m^{-2}hr^{-1}$ (KMTH) for different infrared emissivities (IREM) is illustrated below.



REFERENCES, UNIT 1.2

INFRARED RADIATION

BOOKS

TYPE	PUBL	CITY	PGES	ANIM	KEY WORDS-----------------	AUTHORS/EDITORS--	YEAR
aubo	haro	nyny	151	----	energy exchnge in biospher	gates,dm	1962
edbo	ugap	atga	95	----	remote sensing in ecology	johnson,pl,ed	1969

SERIALS

CODEN	VO-NU	BEPA	ENPA	ANIM	KEY WORDS-----------------	AUTHORS----------	YEAR
AGJOA	58--6	597	601	----	infra thermometry of veget	fuchs,m; tanner,c	1966
AJBOA	38--5	327	331	----	refl vis, infra rad, leave	billings, wd; mor	1951
AJBOA	51--5	529	538	----	radia and convec in conife	tibbols,ec; carr/	1964
APOPA	7---9	1803	1809	----	sen bio env, port rad ther	gates,dm	1968
ECOLA	49--1	145	147	----	thrm ener exch, tree,night	moen,an	1968
JGREA	64-10	1617	1619	----	var, net exch of rad fo ve	decker,wl	1959
JGREA	65-11	3657	3667	----	economical net radiometer	tanner,cb; busin/	1960
JGREA	67-13	5179	5185	----	energ bal, evap surf, arid	fritschen,lj; van	1962
JRMGA	27--5	401	403	odvi	radint temps hair surfaces	moen,an	1974
JWMAA	32--2	338	344	odvi	surf tmps, radnt heat loss	moen,an	1968
JWMAA	38--3	366	368	odvi	chngs radnt surf temp,wind	moen,an; jacobsen	1974
MMONA	23---	1	43	----	atmospheric radiati tables	elsasser,wm; culb	1960
PSAFA	-----	105	109	----	partition rad heat, forest	knoerr,kr	1964
QJRMA	89---	339	348	----	long wave radi, clear skie	swinbank,wc	1963
SIFEA	113..	1	17	----	heat balance of the forest	dzerdzeevskii,bl	1963
XANEA	84---	1	24	----	rad mea and op for instrum	lull,hw; reigner,	1967
XIPPA	269..			----	energy budget studies	anderson,er	1954

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Budyko, M. I. 1956. The Heat Balance of the Earth's Surface. (Translated for the U.S. Weather Bureau, 1958). Leningrad. 259 p.

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:

$$QREE = (SBCO)(ERTK)^4$$

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

Equivalent temperatures in Celsius and Kelvin degrees are:

-40 C	=	233.16 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

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