

Lecture 5, Solar Radiation, Part 1, Principles

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This set of Lectures will discuss

- A. Solar Radiation
 - 1. Solar Constant
 - 2. Spectral Composition of Sunlight
 - a. Planck's Law
 - b. Wien's Law
 - c. absorption, reflection and transmission
 - d. uv,PAR, NIR, IR

L5.1 Introduction

The sun is the source of energy that drives the cycle of life and death on earth. It is also the energy source that gives us warmth and evaporates water and melts snow. Obviously, no course on biometeorology could proceed without a thorough discussion of solar radiation.

The sun is our nearest star. It is about 150,000,000 km away from the Earth. Due to its immense, but finite size, it has an angular diameter of 0.5 degree (32 minutes), as viewed from Earth. The Sun burns continuously via thermonuclear reactions (fusion). Inside the sun, radiative processes transfer this energy from 0.3 to 0.7 radii. Convection transfers solar energy to its exterior surface. Despite the extremely high temperatures needed at the core of the sun, to sustain its thermonuclear reactions, the sun has a black body temperature of 5770 K. Consequently, we receive a relatively constant flux density of energy, defined as the **Solar Constant**. Its mean value is **1366 W m⁻² +/- 3¹**.

¹ One Watt is a Joule per second. A Joule is a common unit of energy. It equivalent to the amount of work done. Work is equal to force (mass (kg) times acceleration (m s⁻²) applied over a distance (m)). In sum a Joule is defined as a Newton-meter and can be expressed in terms of kg m² s⁻².

Table 1 Solar Properties (Lean, 1997) the sun course (http://www-solar.dcs.st-andrews.ac.uk/~alan/sun_course/solar.html)

| Property | Value |
|-----------------------------------|---|
| Age | 4.5×10^9 years |
| Magnitude | 4.8 |
| Mass | 1.99×10^{30} kg |
| Radius | 696,000 km |
| Mean Distance from Earth (1 AU) | 1.50×10^{11} m (8 light minutes) |
| Surface Gravity | 274 m s^{-2} |
| Effective Temperature | 5785 K |
| 1 arc second | 726 km |
| Luminosity | 3.86×10^{26} W |
| Solar constant, viewed from Earth | $1366 \pm 3 \text{ W m}^{-2}$ |

The sun emits a **spectrum** of electromagnetic radiation. **Electromagnetic Radiation** consists of discrete packets of photons. Radiation is an electromagnetic mechanism that allows energy to be transported, at the speed of light, through regions of space devoid of matter. **Radiation** is the 3rd manner by which energy is transferred: **convection** and **conduction** being the other means. Radiant energy transfer is not dependent upon contact between the source and sink, as are conduction and convection. Consequently, radiative transfer is much different for the other forms of mass, heat and momentum transfer, that we deal with and are proportional to driving gradients. Electromagnetic radiation moves at the speed of light, c , $2.998 \times 10^8 \text{ m s}^{-1}$, in a vacuum, with wave-like motion. The speed of light is proportional to the product of the wavelength of the radiation (λ) and the frequency at which it oscillates (ν), $\lambda \nu = c$.

Radiation has origins in the absorption and release of energy by electrons. Molecules possess energy in the form of kinetic energy and electrostatic potential energy due to the orbiting of electrons around the nucleus. Molecules also possess rotational and vibrational energy. According to quantum mechanics theory, unique electron configurations occur around each nucleus. The energy level is due to the orbit, and the vibration and rotation of the electrons. A molecule will transfer to a higher energy level by absorbing electromagnetic radiation. Electromagnetic radiation is emitted when electrons drop an energy level. The radiation energy emitted is in discrete packets, called **photons**. A spectrum of radiation is emitted because the excitation of electrons differs when they are associated with rotational, vibration and electronic states of the molecules and atoms.

L5.2 Solar Radiation and Its Spectrum

The Sun emits a nearly continuous spectrum of energy, ranging from very short wave and high energy packets of quanta, to low energy and long wave lengths. Table 5.1 lists the various wave bands that are intercepted by Earth and their sources.

Solar Radiation Spectrum

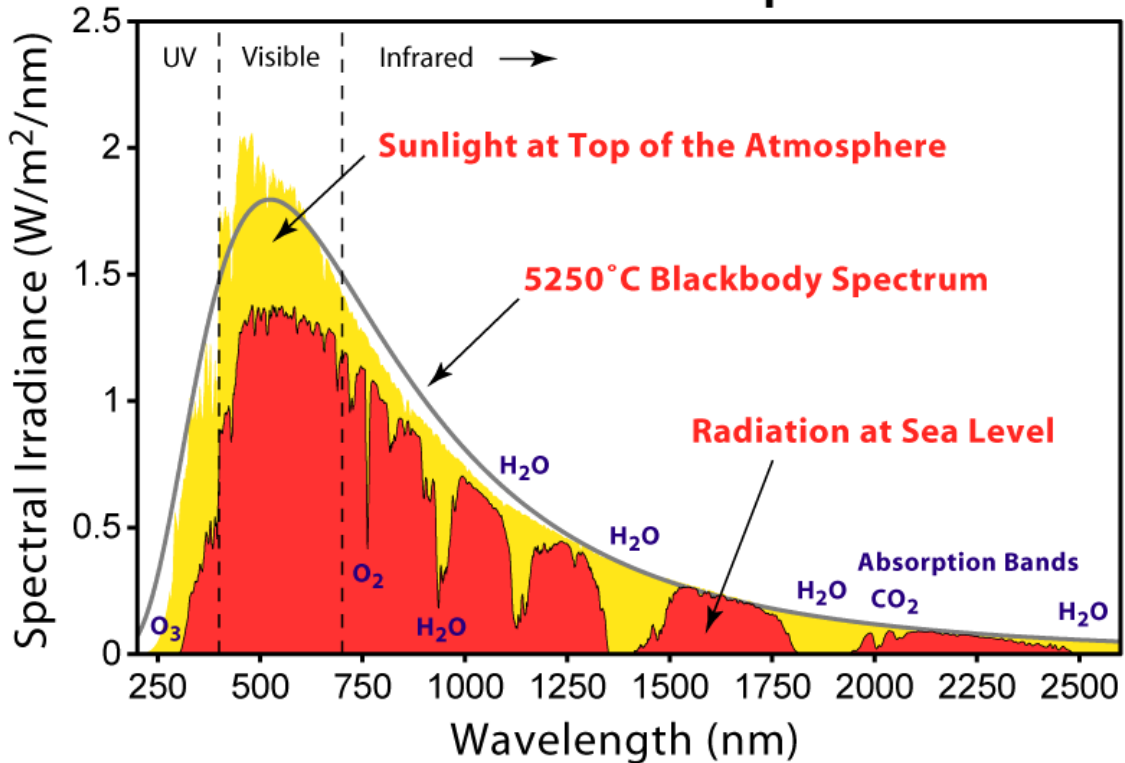


Figure 1 *Electromagnetic spectrum of sunlight above and below the atmosphere.*
www.Globalwarmingart.org

(Web page for radiation calculations
<http://arm.mrcsb.com/sbdart/>)

Table 2 *Various spectral wavebands have different sources of origin*

| Name | waveband | Mechanism |
|---------------|-------------------|--|
| Radio waves | Mm to km | Electrical conductor carrying alternating energy |
| Far infrared | 2.7 to 100 micron | Molecular rotation |
| Near infrared | 0.7-2.7 micron | Molecular vibration |
| Visible | 0.4 to 0.7 micron | Displacement of outer electrons of an atom |
| Ultraviolet | Sub micron | Displacement of outer electrons of an atom |
| Xrays | | Displacement of inner electrons of an atom |
| Gamma rays | Angstroms | Displacement of nucleons in an atomic nucleus |

On earth, there are 4 wavebands of electromagnetic radiation that are of particular interest. These are the **ultraviolet, photosynthetically active, near infrared and infrared** bands (Ross, 1980)

1) **Ultraviolet** (0.29 to 0.38 μm).

This band possess high energy. It can damage molecular bonds. Its presences leads to the photochemical formation of ozone in the troposphere. It has a moderate impact on photomorphogenesis. Its flux density is relatively low since most ozone is absorbed in the stratosphere. Therefore, about zero to 4% of incoming solar radiation is in this band.

2) **Photosynthetic Active band** (PAR), also known as photosynthetic photon flux density (PPFD) (0.38 to 0.71 μm)

This spectral band is the *visible* band. It contains visible energy across the primary colors of purple, blue, green, yellow, orange, red. It provides the energy for photosynthesis. Between 21 and 46 per cent of solar radiation is in this band.

Table 3 color and waveband, nm

| Color | Waveband |
|--------|----------|
| violet | 400-450 |
| Blue | 450-500 |
| Cyan | 500-550 |
| Green | 550-580 |
| Yellow | 580-600 |
| Orange | 600-650 |
| Red | 650-700 |

3) **Near Infrared band** (NIR) (0.71 to 4.0 μm). This wave band is not visible, but contributes to the heat budget of organisms.

4) **Long wave or terrestrial radiation** (3.0 to 100 μm). This is the radiation emitted by bodies on earth. Its flux density is a function of the surfaces temperature and emissivity. Any body warmer than 0 K emits radiation.

Table 4 Distribution of Solar energy by Waveband (Monteith and Unsworth)

| Waveband | Energy % |
|--------------------------------|----------|
| 0-300 | 1.2 |
| 300-400, ultra-violet | 7.8 |
| 400-700, visible/PAR | 39.8 |
| 700-1500, near infrared | 38.8 |

| | |
|-------------------------|------|
| 1500 to infinity | 12.4 |
|-------------------------|------|

The spectral quality of light incident to the ground is affected by selected absorption by water vapor gases and aerosols. Water vapor is a strong absorber of light with wavelengths of 100, 1400, 1600 and 1900 nm. Ozone absorbs ultraviolet light ($\lambda < 300$ nm), CO₂ absorbs strongly in the 2750 and 4250 nm bands and oxygen absorbs 690 and 760 nm sunlight (Bonhomme, 1995).

The spectral quality of sunlight varies with the direct/diffuse fraction of sunlight and the solar elevation angle. Ross (1976) provides an algorithm for the conversion factor between PAR and R_g as a function of the direct beam and diffuse components (this algorithm is for daily integrated fluxes of solar energy):

$$f_{par:R_g} = \frac{0.60 + 0.42 R_{beam} / R_{diffuse}}{1 + R_{beam} / R_{diffuse}}$$

On a clear day with 10% diffuse radiation, $f_{par:rg}$ is 0.438. On a cloudy day with 90% diffuse radiation, $f_{par:rg}$ is 0.582.

On an hourly basis, the PAR:R_g ratio, for direct radiation, ranges from 0.2 to 0.43 as solar elevation goes from 0 to 40 degrees. It then remains relatively constant with higher elevation angles. For diffuse radiation, this ratio ranges from about 0.6 to 0.75. As a quick rule of thumb, the PAR:R_g, for total radiation, is rather conservative, being on the order of 0.46 to 0.50 (these computations assume that PAR conversion factor between quanta and energy is 4.6 umol quanta per J).

Electromagnetic radiation is measured or quantified, interchangeably in terms of quanta or energy. Therefore, certain terminology is used to describe the transfer of this energy to the surface.

Table 5

| Term | symbol and unit | Description |
|---------------------|---|---|
| number of photons | Mole | 6.023×10^{23} photons |
| photon flux | mole s ⁻¹ | dQ/dt |
| photon flux density | mole m ⁻² s ⁻¹ | net radiant flux per unit area, normal to the area |
| photon intensity | mole s ⁻¹ st ⁻¹ | radiant flux through a solid angle |
| photon radiance | mole m ⁻² s ⁻¹ $\frac{1}{\cos \theta} \frac{dI}{da}$ | radiant flux pass through a unit area of surface in the direction of the unit solid angle |
| photon irradiance | mole m ⁻² s ⁻¹ | number of photons incident on a surface per |

unit area and time

Table 6

| term | symbol and unit | Description |
|----------------------|--|---|
| radiant energy | Q (J) | Energy |
| radiant flux | $J s^{-1}$ | dQ/dt |
| radiant flux density | $J m^{-2} s^{-1}$ | net radiant flux per unit area, normal to the area |
| radiant intensity | $J s^{-1} sr^{-1}$ | radiant flux through a solid angle |
| radiance | $J m^{-2} s^{-1}$ $\frac{1}{\cos \theta} \frac{dI}{da}$ | radiant flux pass through a unia area of surface in the direction of the unit solid angle |
| irradiance | $J m^{-2} s^{-1}$ | energy incident on a surface per unit area and time |

(note: solid angle, $d\omega = \frac{dA}{r^2}$)

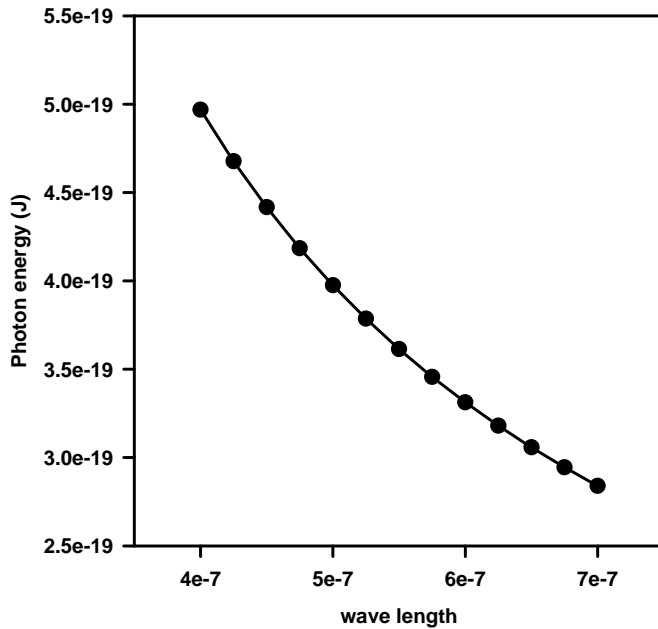
intensity (Watts per steradian)

$$I = \frac{dF}{d\omega}$$

The relation between energy and the wavelength or frequency of light, attributed to Planck, is:

$$E = h\nu = hc / \lambda_{vacuum}$$

where h is Planck's constant, 6.626×10^{-34} J s,



photoen.spw
7/22/99

Figure 2 spectra of energy with wavelength

Mean wavelength of sunlight is about 550 nm. This sunlight has a photon energy of $2.15 \times 10^5 \text{ J mol}^{-1}$. The inverse of this value yields a convenient conversion coefficient between photon flux density and radiant flux density ($4.6 \mu\text{mol J}^{-1}$).

L5.2.1 Radiation Laws attributed to Planck's, Stefan-Boltzmann and Wein

Planck's Law is one of the most important concepts in modern physics. It has much importance for biometeorology for it gives us information about the spectral emission of energy from the Sun.

Planck's Law's defines the amount of energy emitted as a function of the temperature and the wavelength of the source with units of $\text{J m}^{-3} \text{ s}^{-1}$. It's essentially a probability distribution for the change in energy with a respect to the change in wavelength:

$$\frac{dE(\lambda, T)}{d\lambda} = E^*(\lambda, T) = \frac{2\pi hc^2}{\lambda^5 (\exp(\frac{hc}{\lambda kT}) - 1)}$$

k is the Boltzmann constant, $1.3806503 \cdot 10^{-23} \text{ kg m}^2 \text{ s}^{-2} \text{ K}^{-1}$ or (J K^{-1})

Mathematical manipulation of Planck's Law yields useful insights about the transfer of electromagnetic radiation. **Integrating** Planck's distribution with respect to wavelength, for instance, yields the **Stefan-Boltzmann Law**, which states that the radiant energy emitted by a surface is proportional to its **temperature** taken to the **fourth power**.

$$\int E^*(\lambda, T) d\lambda = L = \sigma T^4 \text{ (W m}^{-2}\text{)}$$

σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$). This equation is especially useful for it helps us gauge the radiative temperatures of the sun.

Luminosity equals the solar constant, measured at the Earth's surface times the area of a sphere with a radius equal to the distance between the earth and sun.

$$L = S_s \cdot 4\pi R^2$$

$$L = 1366 \times 4 \times 3.1415 \times (1.50 \cdot 10^{11})^2 = 3.9 \cdot 10^{26} \text{ W}$$

Knowing that that radius of the sun is $6.69 \cdot 10^8 \text{ m}$, we can form a balance between the black body radiation law and the emittance of the sun, to calculate its temperature

$$\sigma T^4 = \frac{3.9 \cdot 10^{26}}{4\pi r^2}$$

yields a surface temperature of 5770 K.

By examining the sun's or Earth's spectrum we are inclined to ask, what is the wavelength of that radiating source when E is maximal? This question can be answered with Wien's Law. **Wien's Law** is derived by examining the **maximum** of a function.

This equation is derived by solving for wavelength when the partial derivative of Planck's Law with respect to wavelength equals zero:

$$\frac{\partial E^*(T, \lambda)}{\partial \lambda} = 0$$

The solution yields:

$$\lambda_{max} = \frac{2897}{T_k} \text{ (\mu m)}$$

For the case where the sun is about 5700 to 5800 K, the maximum wavelength is 483 nm which falls in the blue-green portion of the spectrum.

Climatological records show that the mean earth surface temperature is about 288 K, therefore the earth emits radiation at 10 um, which is in the infrared portion of the electromagnetic spectrum.

L5.2.2 Photon Interactions with the Surface

When photons, interacting with material, are either absorbed (as with a black surface), reflected (as with a bright white surface) or transmitted (as with the passage of sunlight through glass).

Absorptivity: the fraction of incident radiation flux absorbed by a surface

Reflectivity: the fraction of incident radiation flux density that is reflected by a surface

Transmissivity: the fraction of incident radiation flux density that is transmitted through a surface.

Since the absorptivity, reflectivity and transmissivities are fractions of incident sunlight, their sum, with respect to their behavior for a given wavelength, equals one.

$$\alpha(\lambda) + \rho(\lambda) + \tau(\lambda) = 1$$

Because E is not a linear function of wavelength, the average reflectance, absorptance and transmittance must be determined by weighting a surface's reflectance according to the light spectrum, to compute these variables across a broad band portion of the spectrum.

$$\bar{\rho} = \frac{\int \rho(\lambda)E(\lambda)d\lambda}{\int E(\lambda)d\lambda}$$

$$\bar{\alpha} = \frac{\int \alpha(\lambda)E(\lambda)d\lambda}{\int E(\lambda)d\lambda}$$

$$\bar{\tau} = \frac{\int \tau(\lambda)E(\lambda)d\lambda}{\int E(\lambda)d\lambda}$$

The reflectance in the visible portion of the EM spectrum is called albedo. Typical values for common surfaces are listed below

L5.2.3 Albedo

Albedo is not only the name of our dog, but it is defined as the fraction of incident radiation that is reflected by a surface. It is derived from the Latin word *albus* for white.



Figure 3 Albedo I.

A reflectance spectrum taken of Albedo proves this, showing very high reflectance for the whole visible waveband of the electromagnetic spectrum.

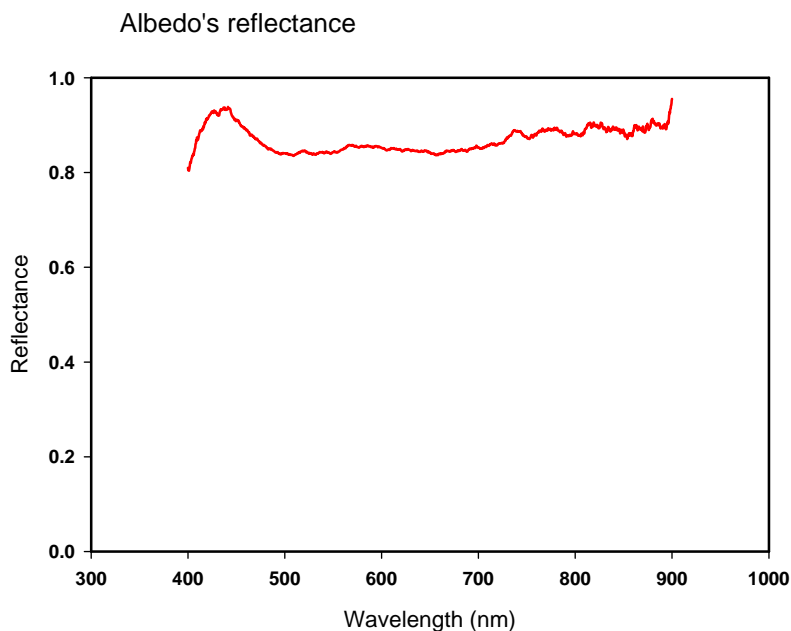


Figure 4 Reflectance spectra taken of Albedo.

In meteorology, **albedo** is a fundamental parameter used in weather models and models that compute the radiative balance of the Earth's surface. The Earth, as viewed from space, has an albedo of 30%.



Figure 5 Picture of Earth from space

The albedo of different vegetation surfaces varies widely. Deserts and snow are highly reflective, as seen in Figure 5. By contrast, forests are optically dark. Crops and short vegetation tend to have medium albedos.

Table 7 List of Reflectances for a range of vegetation and soil types (Campbell and Norman, 1998, Davies and Idso, 1979(Oke, 1987))

| Surface | Reflectivity |
|-------------------------|--------------|
| Grass | 0.17-0.28 |
| Wheat | 0.16-0.26 |
| Maize | 0.18-0.22 |
| Beets | 0.18 |
| Potato | 0.19 |
| Rain Forest | 0.12 |
| Deciduous forest | 0.10-0.20 |
| Coniferous forest | 0.05-0.15 |
| SubArctic | 0.09-0.20 |
| Savanna | 0.16-0.21 |
| Steppe | 0.20 |
| Fresh snow | 0.75-0.95 |
| Old snow | 0.40-0.70 |
| Wet dark soil | 0.08 |
| Dry dark soil | 0.13 |
| Dry sand | 0.35 |
| Boreal forest with snow | 0.12-0.30 |

Newer measurements of albedo from space and networks of flux towers enable us to rank albedo by plant functional type, with mean values, averaged over a year ranging between 0.1 and 0.2. Evergreen needleleaved forests (ENF) have the lowest albedo, followed by wetlands (WET), mixed forests (MF), deciduous broadleaved forests (DBF), woody savanna (WSA), evergreen broadleaved forests (EBF), savanna (SAV), crops (CRO), grasslands (GRA) and open shrubland (OSH). Note these values will vary seasonally as there are changes in leaf area, wet and dry soils, and the presence and absence of leaves and snow.

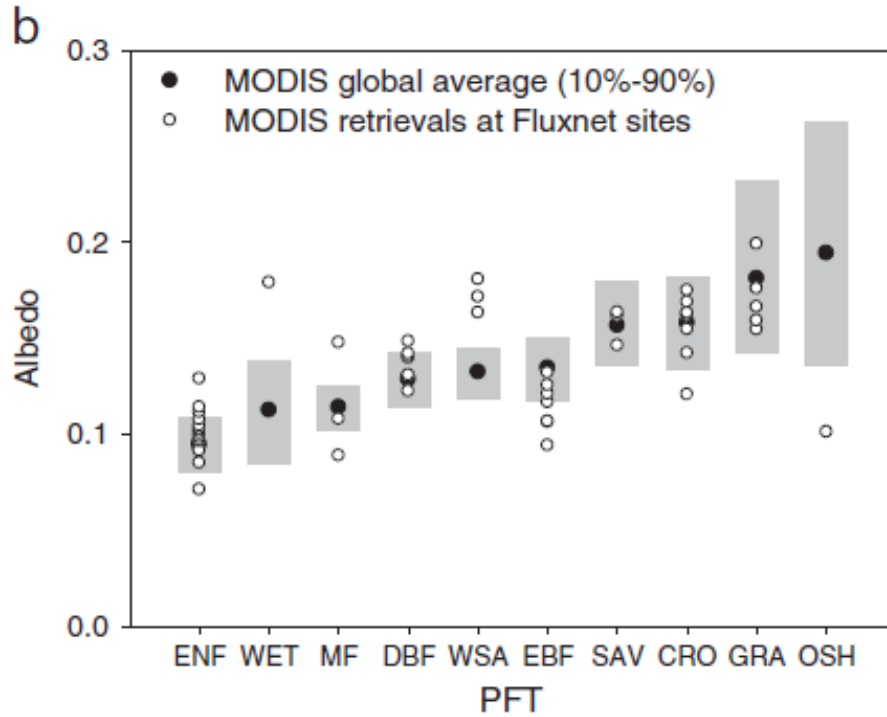


Figure 6 Mean yearly values of albedo by plant functional type (Cescatti et al., 2012)

The role of snow and forest landscapes is particularly interesting. The presence of snow in the Boreal zone does not lead to as bright an albedo as was presumed by weather forecasters.

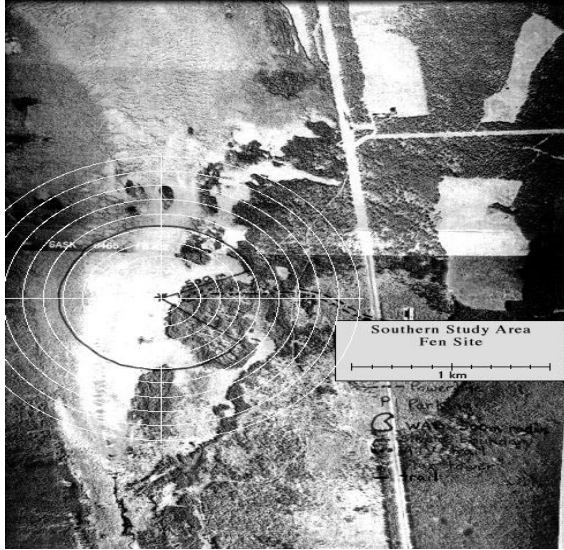


Figure 7 Snow covered fen and adjacent black spruce forest. Notice the bright fen, as it consists of low level herbaceous vegetation. In contrast the adjacent spruce forest is quite dark, despite the presence of snow. Boreas project

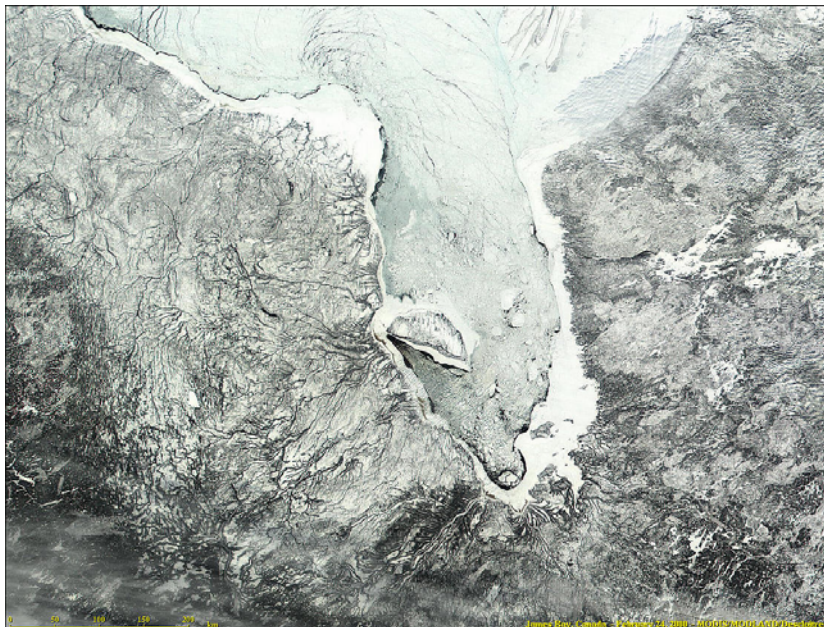


Figure 8 James Bay, Canada, MODIS Satellite.

Notice the dark spots from the interception of light by the boreal forest, even though the landscape is covered with snow, a larger scale example of the one demonstrated in Figure 5.
<http://modland.nascom.nasa.gov/gallery/?JamesBay.A2000055.1645.1110x840.jpg>



Figure 9 Dark, low albedo of old age redwood stand, next to clear cuts and forest regrowth. Orick, CA.

In this situation, we can observe how albedo decreases with canopy rugosity (Figure 9) (Ogunjemiyo et al., 2005).

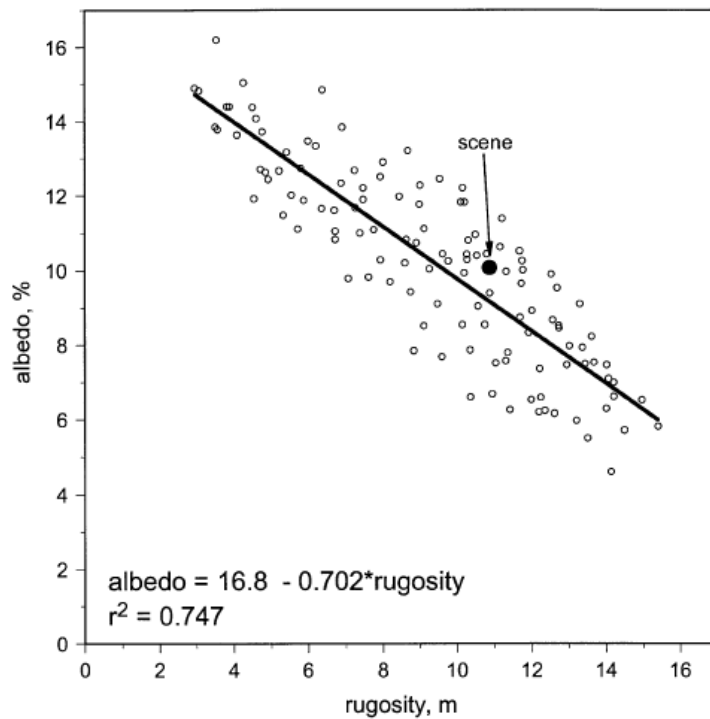


Figure 10 Albedo and canopy rugosity (Ogunjemiyo et al., 2005)



Figure 11 Brighter landscape of oak savanna, open vegetation with dead and highly reflective grass underneath.

In the BOREAS experimental region, the winter background albedo of the forest is on the order of 0.12 to 0.30, while over grass it was 0.70. Computations of temperature using an older version of the European Center Medium Range Weather Forecasting (ECMWF) model predicted temperatures that were up to 10°C too cold, as they assumed that a forest with snow was highly reflective. When the regional albedo was reset to 0.2 there became good agreement between measured and forecasted temperatures.

Life history is another issue affecting albedo. Figure 11 shows the reflectivity of visible light over a grazed grassland when it was green and photosynthesizing and dead and dry. Albedo more than triples, at midday, when the grass changes from being green and dry.

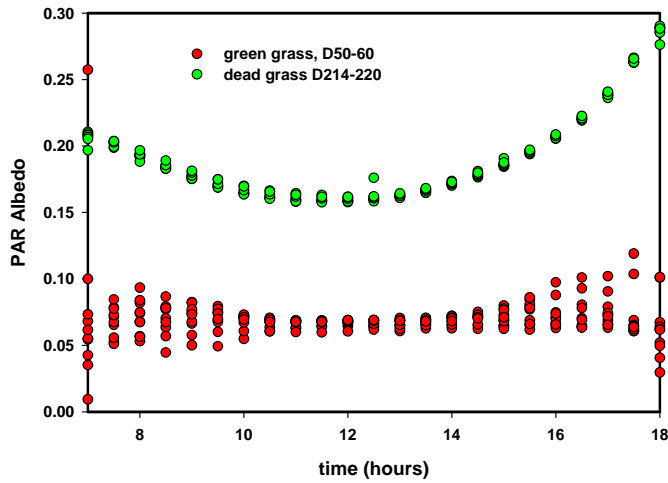


Figure 12 Reflectivity of visible light (photosynthetically active radiation) over a grazed grassland near Ione, CA.

5.3 Hyperspectral Albedo and Ecological Function

The broadband reflectance can be broken down into its spectral components. Here we see a seasonal transition and observe the fact that different portions of the spectra vary, due to the presence and absence of plant pigments, soil moisture, crop health etc.

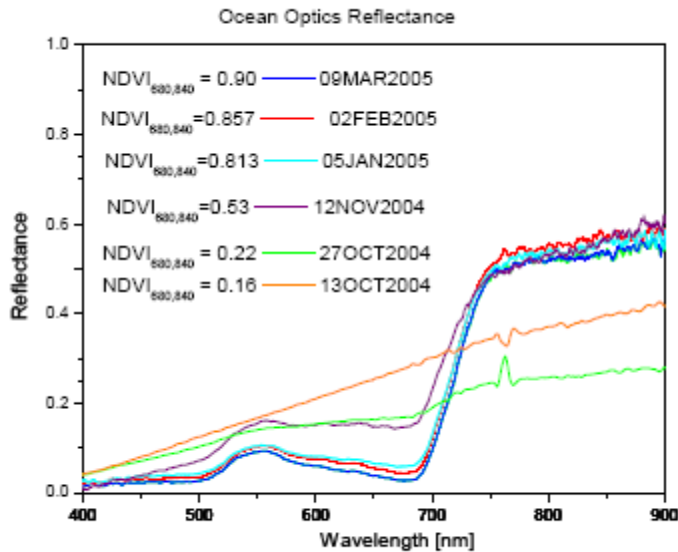


Figure 13 Reflectance spectra of an annual grassland. Unpublished data of M. Falk, D. Baldocchi and S. Ma.

Recent analyze by Ollinger et al (Ollinger et al., 2008) and Hollinger et al (Hollinger et al., 2010) have shown a strong relation between spectrally selected reflectance bands and leaf nitrogen (Figure 13). Hence by measuring albedo from space one can produce spatial maps of leaf nitrogen for a range of ecosystems (Figure 14).

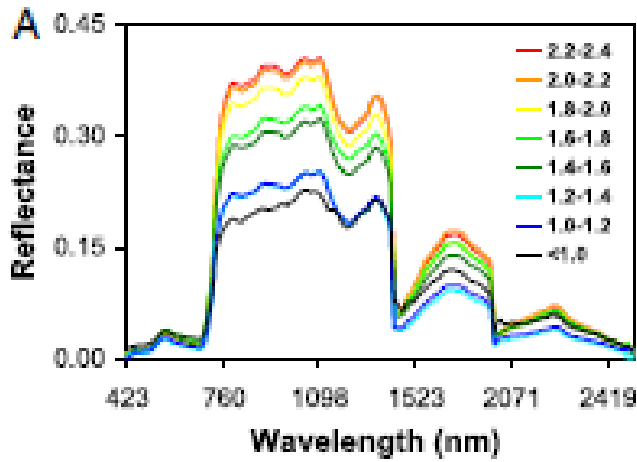


Figure 14 after Ollinger et al. Hyperspectral reflectance and classes of leaf nitrogen

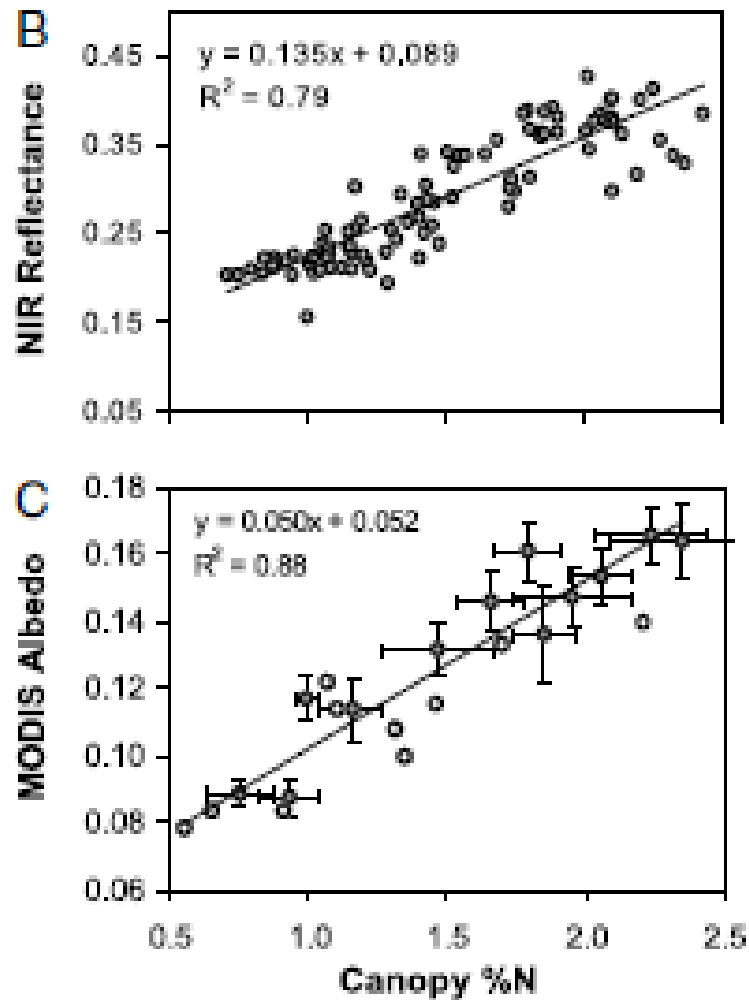


Figure 15 Ollinger et al. 2008

SUMMARY

- Planck's Law defines the spectral distribution energy radiating of a black body surface of a given temperature.
- The main broadband wave bands of solar energy are ultraviolet, visible and near infrared.
- Integrating Planck's Law with respect to wavelength from zero to infinity produces the Stefan-Boltzmann Law which states that the amount of energy

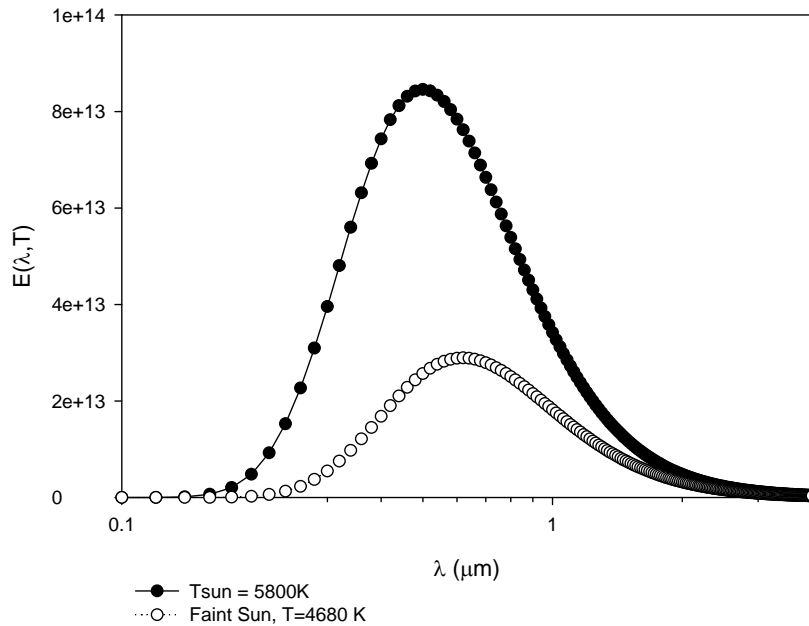
radiating from a black body is proportional to its temperature to the fourth power.

- Differentiating Planck's Law with respect to wavelength and solving for the maximum value (the wavelength when the derivative is zero) produces Wien's Law, which states that the maximum wavelength is inversely proportional to surface temperature
- One can derive how hot the sun is by knowing its spectral distribution and solving for Wien's Law. It can also be derived from geometrical considerations knowing the solar constant, the distance between Earth and the Sun, the Sun's radius and the Stefan-Boltzmann law.
- Incident radiation is absorbed, reflected or transmitted.
- The albedo of land is a function of vegetation leaf area and height, soil exposure, and its moisture content.

Points to Ponder

The Figure below shows the spectral distribution of sunlight for current conditions and pre-historic times. There are some interesting relationships between the spectral output of radiation and the co-evolution of vision (Fernald, 2006), life (Marais and Walter, 1999) and photosynthesis (Clegg et al., 1994).

1. Note the correspondence between the current spectral peak and the range over which we see.
2. Note the correspondence between the spectral peak of the faint sun and the pigments that evolved for photosynthesis, that use 680 and 720 nm radiation.



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Data Resources

Sunphotometer data and atmospheric optical depth information

<http://aeronet.gsfc.nasa.gov/>

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