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Solar Flux and Albedo

1.1 Introduction

The intensity or flux of solar radiation crossing a unit area at the Earth's orbit (1 astronomical unit (A.U.) from the Sun) is called the solar constant and will be denoted by $E_{\oplus}$. $E_{\oplus}$ is the radiation striking unit area if the rays are normal (or perpendicular) to the surface. However, if the rays are not normal to the surface, then they are spread out over a greater effective area. If we define the angle θ between the normal to the surface and the direction to the light source (e.g. sun), then the flux is diluted by the factor $\cos(\theta)$ as shown in Figure 1. If the ground is flat and level then the angle θ is just the solar zenith angle (SZA), i.e. the angle between the zenith (directly overhead) and the direction to the sun.

Solar radiation enters the atmosphere as a plane-parallel beam as shown in Figure 2. Some of the light passes through unattenuated such as ray 4 in Figure 2 while some scatters off air molecules (labeled M) and aerosols (particles, labeled P) as shown by rays 3 and 2 respectively. Depending on the weather some radiation may be scattered off or be transmitted by clouds as illustrated by rays 1 and 5. Finally, some of the radiation that reaches the surface and is reflected may itself be scattered back down as shown by ray 6. Of these various types of rays we identify those that are unscattered, such as ray 4, as the direct beam, while the remainder we call the **scattered radiation**.

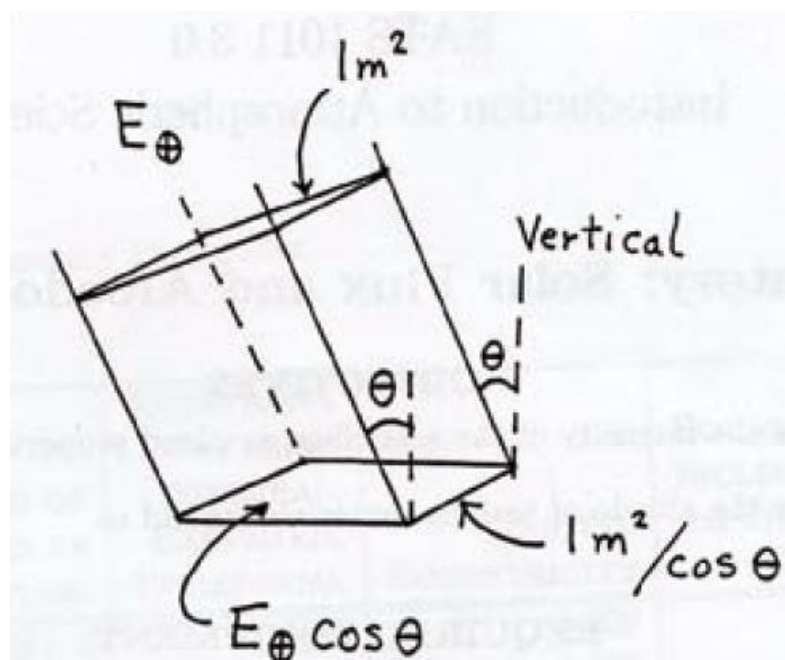


Figure 1 - Solar flux incident on a surface at a SZA of θ . Notice that the flux at the surface is $E_{\oplus} \cos \theta$.

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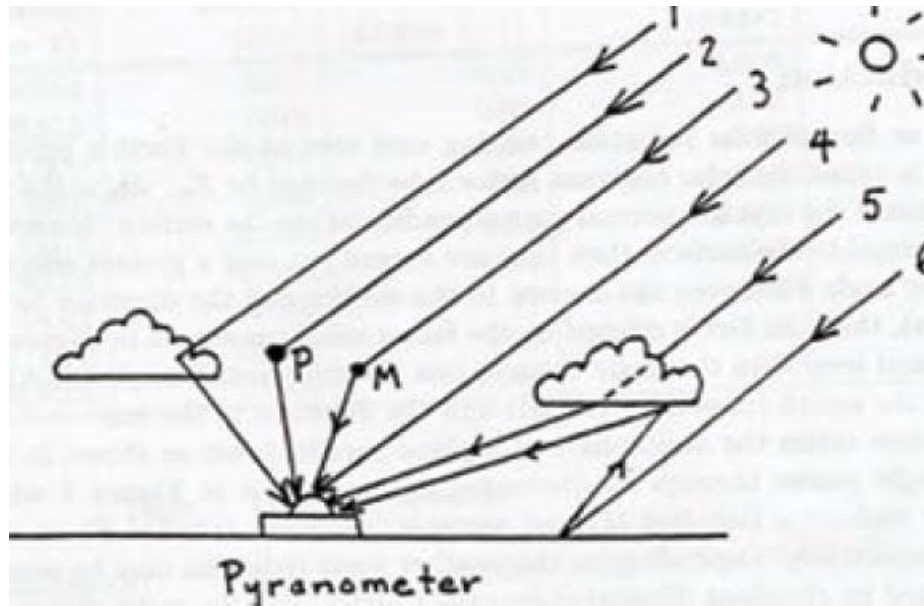


Figure 2 - Scattering of solar radiation within the atmosphere

The albedo, B , of a material is the fraction of light incident that is reflected from a surface, and can be expressed as:

$$B = \frac{\text{flux of reflected radiation}}{\text{flux of incident radiation}} \quad [1]$$

It can be a function of the angle of incidence of the radiation, the angle at which the reflected radiation is measured, and the wavelength. You have seen during the lectures that the albedo of a planet is critical in terms of the amount of energy that is absorbed from the incident solar flux. For our Earth at least half the energy is reflected from clouds while the remaining is reflected from water, plants, soil etc. As the surface of the planet changes due to deforestation, changing farming methods, changing climate (desertification, cloud or ice/snow coverage), etc. it is important to know how the albedo of the planet may change. In addition, the reflectivity of many materials on the Earth's surface changes with wavelength and so it becomes possible to detect the type of rocks, or soil, or types of trees in the forest from aircraft or from satellite. Thus, it becomes important to be able to measure albedos of various materials.

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EMOS York University Weather station

During this exercise we won't be able to measure irradiance by the use of a pyranometer and multimeter however, we will utilise irradiance that has already been measured for us at the EMOS weather station which is located at York University. For a brief background on the EMOS weather station follow the link <https://www.yorku.ca/pat/weatherStation/background.html> . Below (figure 3) is the image of the EMOS weather station.



Figure 3: EMOS York University weather station (left) and solar and far infrared radiation balance radiometers (right), (image taken by: Prof. Chen)

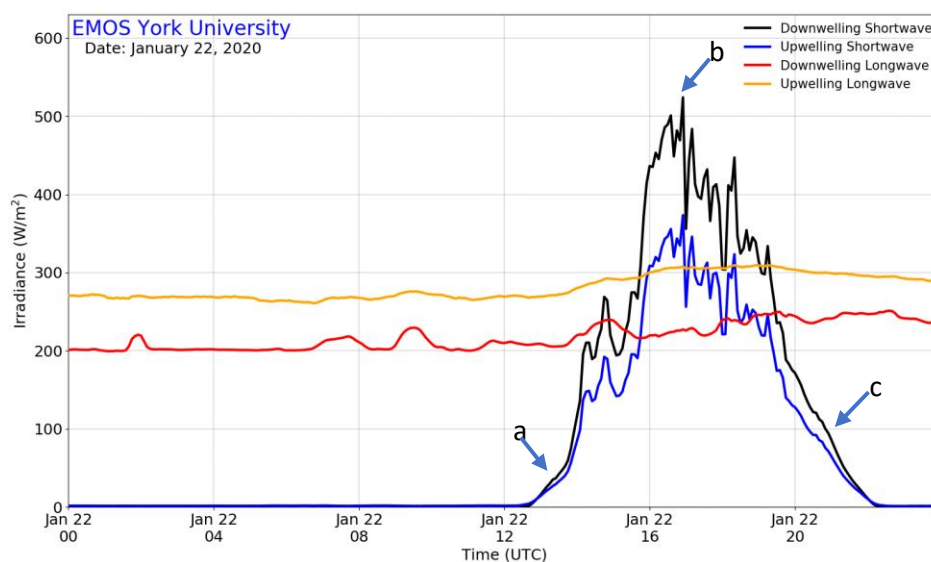
Exercise 1

Figure 4: Irradiance at York University weather station. Source: <https://www.yorku.ca/pat/weatherStation/index.php>

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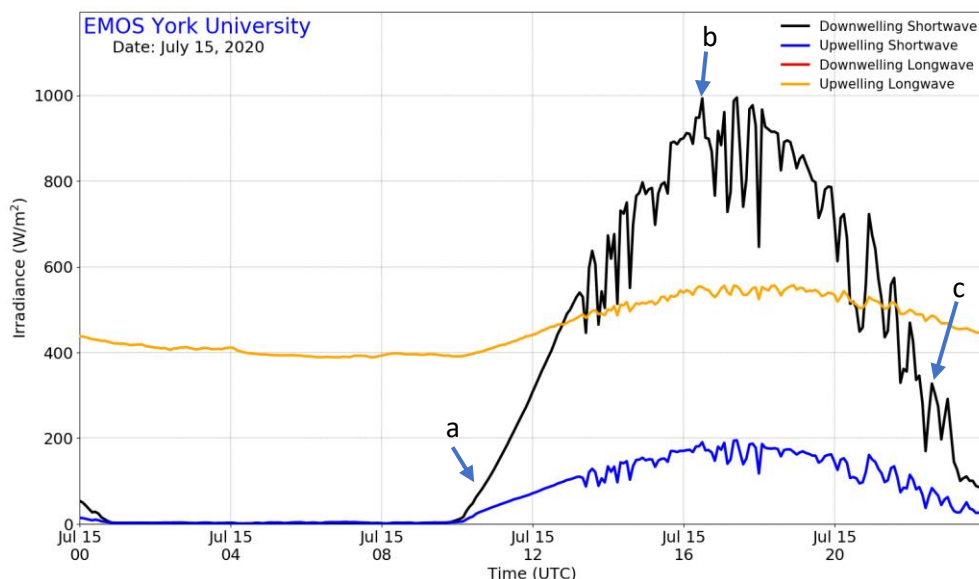


Figure 5: Irradiance at York University weather station. Source: <https://www.yorku.ca/pat/weatherStation/index.php>

Study the figures above and answer the following questions. [31 marks]

- Determine sunrise over EMOS York University weather station in UTC and local time. [2 marks]
- Determine the time that maximum downwelling Shortwave occurred. [2 marks]
- Why is the Downwelling shortwave higher in figure 5 compared to figure 4. [4 marks]
- Explain why Downwelling Shortwave graph has sudden drops in irradiance. [5 marks]
- Why does upwelling Longwave in figure 4 does not vary as much as in figure 5. [4 marks]
- Estimate sunset in both figures in UTC and local time. [3 marks]

Estimate B, albedo at this station for the following times indicated by a, b and c, fill the following table, show your calculations. Use the formula, $B = \frac{\text{Upwelling shortwave}}{\text{Downwelling shortwave}}$ [6 marks]

Location	22 January 2020/figure 4	15 July 2020/figure 5
a.		
b.		
c.		

- Compare the albedos you obtained at location (b) above for both location and give an explanation why they are different and what does a higher value of albedo means. [5 marks]

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1.2 Blackbody Radiation

If a planet is at a distance D from the sun, which has luminosity $L = 3.846 \times 10^{26} \text{ W}$ (assuming the sun radiates isotropically and the planet is far away from the sun), then the power absorbed [W] by the planet is given by

$$P_{abs} = \frac{Lr^2(1 - B)}{4D^2} \quad [2]$$

Here r^2 is the radius of the planet and B is the planetary Bond albedo. If we assume that the entire planet is at temperature T_e and acts as a blackbody, the power radiated back to space by the planet is

$$P_{rad} = 4\pi r^2 \sigma T_e^4 \quad [3]$$

Where $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is the Stefan-Boltzmann constant. Equating equation [2] and [3] and solving for T_e gives the effective temperature (in K) as:

$$T_e = \sqrt[4]{\frac{L(1-B)}{16\pi\sigma D^2}} \quad [4]$$

Using a distance for Earth of $D = 1 \text{ A. U.} = 1.5 \times 10^{11} \text{ m}$ and a Bond albedo of $B = 0.3$ gives an effective temperature of

$$T_e = \sqrt[4]{\frac{3.846 \times 10^{26} \text{ W} (1 - 0.3)}{16\pi(5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4})(1.5 \times 10^{11} \text{ m})^2}} = 255 \text{ K}$$

Exercise 2: Blackbody Radiation (10 marks)

1. Table 1.3.2 contains planetary data for each planet in our solar system.

- (a) Calculate the effective temperatures for each planet listed (except Earth) and compare with the measured surface temperatures as given in Table 1.3.2. (3.5 marks)
- (b) For which planet(s) is this difference the largest? (0.5 marks)
- (c) Explain the reason for the observed difference(s)? (1 mark)

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2. Calculate the power absorbed (in units of watts, W) by Mars and Saturn using equation [2]. Discuss the result. (3 marks)

3. We can use the wavelength of maximum emission or a star's visible color to estimate its temperature. Inversely, we can use the star's temperature to estimate the wavelength of maximum emission, and thus deduce its visible color. This relationship, known as Wein's displacement law is given by

$$\lambda_{max} = \frac{2900 \mu\text{m K}}{T} \quad [5]$$

An observed star has a temperature of $T = 5000 \text{ K}$. Determine the wavelength of maximum emission that corresponds to this temperature using equation [5]. What color in the visible spectrum does this correspond to (refer to table 1.3.3)? (2 marks)

Grand Total = 40

1.3 Useful Information

Table 1.3.1, A – Solar zenith angles for Fall 2020.

Time (EST)	Solar Zenith Angle (°)	
	Tue, Sep 22	Wed, Sep 23
12:00 P.M.	45	46
1:00 P.M.	50	51
2:00 P.M.	58	58
3:00 P.M.	67	68
4:00 P.M.	78	78

Table 1.3.1, B – Depth of cloud, L in units of km for Fall 2020.

Time (EST)	Depth of Cloud, L [km]	
	Tue, Sep 22	Wed, Sep 23

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11:30 A.M. – 2:30 P.M.	3.5	2.5
2:30 P.M. – 5:30 P.M.	4	

*All labs please use $r = 10 \mu\text{m}$ and note that $1 \mu\text{m} = 10^{-6} \text{m}$

Table 1.3.2 – Planetary information.

Planet	Mean Distance From Sun (A.U.)	Bond Albedo	Planetary Equatorial Radius[km]	Observed Surface Temperature [K]
Mercury	0.387	0.056	2425	520
Venus	0.723	0.72	6070	700
Earth	*1.000	0.30	6371	288
Mars	1.524	0.16	3395	220
Jupiter	5.203	0.343	71,300	124
Saturn	9.539	0.342	60,100	95
Uranus	19.18	0.34	25,300	54
Neptune	30.06	0.29	24,600	60

*1 A.U. = $1.5 \times 10^{11} \text{m}$

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Table 1.3.3 – Wavelengths and their corresponding colors in the visible spectrum

Color	Wavelength Interval [μm]	Typical Wavelength (Use “*” value when plotting graph) [μm]
Violet	0.390 – 0.455	0.430
Dark Blue	0.455 – 0.485	0.477*
Light Blue	0.485 – 0.505	0.495
Green	0.505 – 0.550	0.530*
Yellow-green	0.550 – 0.575	0.560
Yellow	0.575 – 0.585	0.580*
Orange	0.585 – 0.620	0.600
Red	0.620 – 0.760	0.640*

Table 1.4.4 – Useful constants

Stefan-Boltzmann Constant, σ	$5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Average Radius of Earth	$6.37 \times 10^6 \text{ m}$
1. A.U, the average distance from Earth to Sun	$1.5 \times 10^{11} \text{ m}$
Luminosity of Sun, L	$3.846 \times 10^{26} \text{ W}$