GEOG 321 - Reading Package Lecture 6

SHORT-WAVE RADIATION BALANCE

In the first reading package it was noted that boundary layer climates respond to processes operating on time scales of less than one day. Therefore, this section outlines the most important general features of the *diurnal course* of short-wave radiative flux densities. This is best accomplished by considering the case of an ‘ideal’ site. Such a location presents the minimum complication being horizontal, homogeneous and extensive. The surface is a flat, moist, short grass located in the mid-latitudes in the warm season. Figure 1 shows the diurnal variation of the short-wave radiation budget at a site close to Vancouver (Westham Island, Delta, BC). Figure 1a shows the radiation flux densities measured in W m^{-2} for a clear-sky day. Figure 1b shows the same graph, but for an overcast day.

Short-wave irradiance. On the clear sky day (Figure 1a), the pattern of incoming shortwave radiation ($K_\downarrow$, *irradiance*) is controlled by the azimuth (Ω) and zenith (Z) angles of the Sun relative to the horizon, with a maximum at local solar noon. In a relatively clean atmosphere approximately 50% of $K_\downarrow$ is in the visible portion of the electromagnetic spectrum. The pattern of shortwave irradiance $K_\downarrow$ is significantly reduced and much more variable due to the cloud cover (Figure 1b). The diffuse fraction increases greatly (not shown). At 16:00 $K_\downarrow$ is even greater than without cloud (and comparable to K_{Ex}) – this is when the sensor receives extra radiation reflected from the sides of scattered cumulus clouds in addition to the direct-beam irradiance.

Short-wave reflectance. The short-wave radiation reflected from the surface ($K_\uparrow$, *reflectance* in W m^{-2}) depends on the amount of irradiance ($K_\downarrow$) and the surface albedo (α):

$$K_\uparrow = K_\downarrow \, \alpha \qquad \star \qquad (3.1)$$

Although α is not a perfect constant through a day, to a first approximation, it is reasonable to expect $K_\uparrow$ to be a reduced mirror-image of $K_\downarrow$.

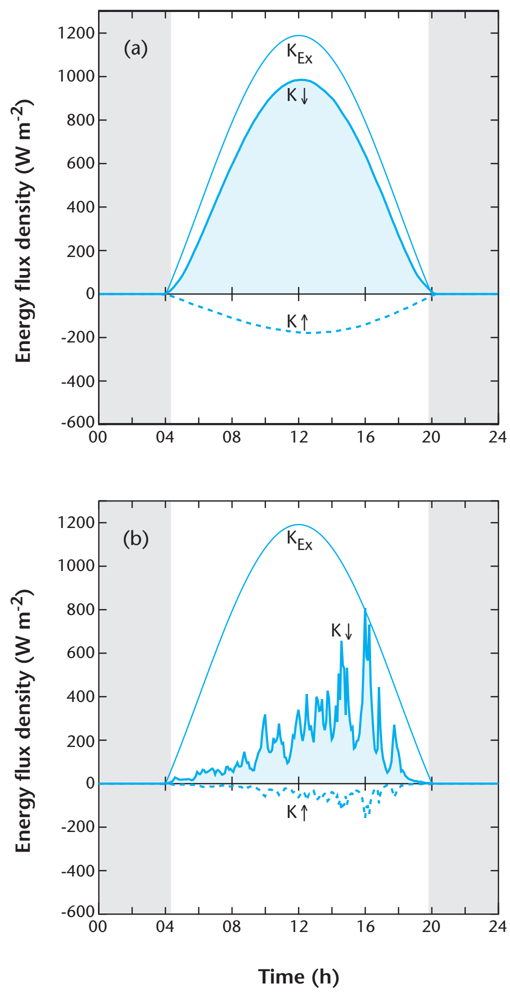

Figure 1: Diurnal course of modelled extraterrestrial irradiance (K_{Ex}), measured short-wave irradiance at the surface ($K_\downarrow$), and measured short-wave reflectance by the surface ($K_\uparrow$) measured for (a) a clear-sky day on June 30, 2009, and (b) on an overcast day on Jun 24, 2009, above a short grass surface at 49°N on Westham Island, Delta, BC.

Given that the surface is opaque to short-wave radiation (i.e. $\Psi = 0$), the portion of $K_\downarrow$ that is not reflected is absorbed, so the net short-wave radiation (K^*) is:

$$K^* = K_\downarrow - K_\uparrow \qquad \star \qquad (3.2)$$

Therefore in our example, where α = 0.2, K^* would describe a curve with positive values of about $0.8K_\downarrow$.

We should also note that there are two types of reflection from surfaces. Radiation can be scattered in a *diffuse* manner, or in a *specular* (or mirror-like) fashion. In the former case there is no directional character; in the latter radiation incident at a given angle is reflected at the same angle. For short-wave beam radiation (S) most natural surfaces act as diffuse reflectors for β greater than 30°, but may become increasingly specular for smaller angles. This is especially true for relatively smooth surfaces such as water, ice, snow, etc. Natural surfaces show very little directionality for diffuse radiation (D). At low β it is also necessary to account for the azimuthal directionality of reflection. Water and snow surfaces show greatest reflection in the direction of the solar beam.

RADIATIVE PROPERTIES OF VEGETATION

Leaves. The shapes of leaves are particularly interesting because they have both upper and lower active surfaces. This greatly increases their effective surface area for radiative exchange, and complicates the one-dimensional framework we have used above to describe a flat 'ideal' surface.

The radiative properties of leaves show an interesting wavelength dependence (Figure 2). Leaves are not opaque to shortwave radiation so that the disposition of incident radiation is given by equation 2.12, and transmission is non-zero. The relative roles of reflectivity (α_λ), transmissivity (ψ_λ) and absorptivity (ζ_λ) are governed by the structure of the leaf interior and the radiative properties of the main plant pigments (especially chlorophyll and carotenoids). The cellular structure tends to cause almost totally diffuse scattering. This results in almost equal portions of the radiation being reflected back and transmitted on through the leaf and explains why the α_λ and ψ_λ curves in Figure 2 are similar in shape. The pigments are particularly effective absorbers in the blue (0.40 to 0.51 μm) and red (0.61 to 0.70 μm) bands of the visible portion of the electromagnetic spectrum, and are at the core of the photosynthetic process. The waveband between 0.40 and 0.70 μm is therefore designated as *photosynthetically active radiation* (PAR, see Reading Lectures 3-4).

Within this range there is a small relative peak of reflection and transmission between 0.5 and 0.55 μm. Since this lies in the green portion of the visible it explains the colour of most vegetation as perceived by the human eye. At 0.7 μm absorption decreases sharply and thereafter gradually increases until about 2.5 μm, beyond which absorption is almost total.

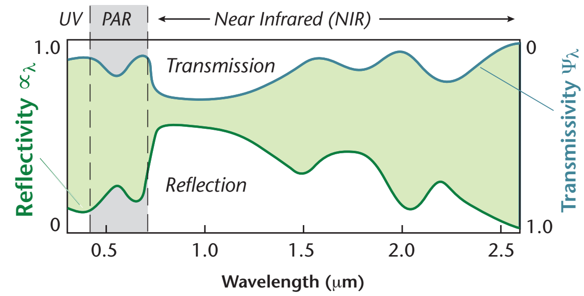

Figure 2: Idealized relation between wavelength and the reflectivity (α_λ), transmissivity (ψ_λ) and absorptivity (ζ_λ) of a green leaf (after Monteith, 1965).

The relationships depicted in Figure 2 provide an almost ideal radiation environment for leaves. In the red and blue portions of the visible, where light is needed for photosynthesis, absorption is good. On the other hand, in the *near infrared* (NIR) high reflectivity enables the leaf to reject the bulk of the incident energy. The heat content of this radiation is very high but it is not useful for photosynthesis, therefore its rejection is helpful in offsetting the heat load on the leaf. The high emissivity at longer wavelengths also helps the leaf to shed heat to the environment and keep leaf temperatures moderate.

Two exceptions to the generalized scheme of Figure 2 are of interest. Many desert plants have thick leaves which reduce or eliminate transmission. They avoid overheating by having higher than normal reflectivity. The needles of coniferous trees also have low transmissivity. Their relief from potentially excessively high temperatures is attributable to their geometry. Due to their small size they exhibit large surface area compared to their mass. Therefore, they are ideally suited to heat exchange but are poor heat storers. This enables them to 'dump' heat to the environment by convection and longwave radiation.

Canopies. A vegetation system is composed of many active surfaces represented by the myriad of leaves making up the foliage, and to a lesser extent the other portions of the plant or tree structure. Faced with such a system it might perhaps seem appropriate to analyse the climate of a typical leaf and then to integrate this over the number of leaves to give the climate of the plant or tree, and then to integrate those climates to arrive at the climate of a crop or forest.

Unfortunately, it is not possible to make such a linear extrapolation of elemental units and thereby to combine many microclimates into a local climate. On a plant or tree the leaf is not in isolation, it is intimately linked to its total environmental setting, and the same is true of a plant or tree in a crop or forest. The effects of mutual shading, multiple reflection, etc. provide important feedbacks not found in the isolated case.

The albedo (α) of a vegetation stand is lower than the value for its individual leaves because reflection depends not only on the radiative properties of the component surfaces, but also upon the stand architecture and the angle of solar incidence. The latter two factors control the amount of penetration, radiation trapping, and mutual shading within the stand volume. Thus although most leaves have an albedo of about 0.30 the albedo of crops and other vegetation communities is less, and to some extent a function of their height. For most agricultural crops and natural vegetation less than 1 m in height the albedo lies in the remarkably narrow range from 0.18 to 0.25. There are however two limitations to this simple picture. First, the values only apply to green vegetation with a full surface cover. If the plants are wilted or dead, or the underlying soil is exposed, the generalization does not apply. Second, the values refer to the albedo in the midday period. Early morning and evening albedos are higher, and when plotted versus the position of the Sun in the sky show a characteristic curve (Figure 3). However, since the highest albedos occur at the times of low energy input the effect of this diurnal variation on the total radiation budget is small. The dependence of albedo upon the solar altitude also explains why tropical albedos are usually less than those for similar surfaces at higher latitudes, and accounts for the observation that the diurnal variation of the albedo is much less with cloudy skies. Its role in explaining seasonal variations of albedo is obscured by changes in plant phenology, snow, etc.

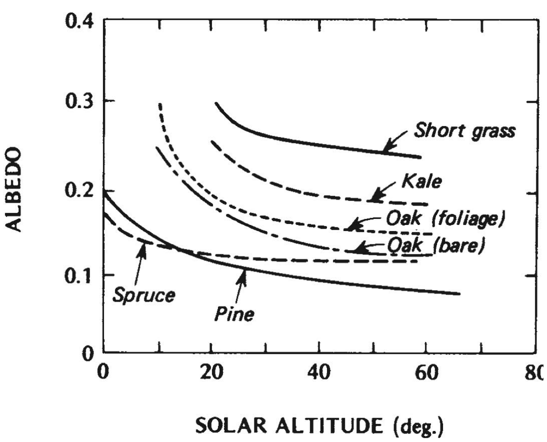

Figure 3: Relation between the albedo of vegetation and solar altitude on sunny days. Grass and kale (Monteith and Szeicz, 1961); oak forest (Rauner, 1976); spruce forest (Jarvis et al., 1976); and Scots pine forest (Stewart, 1971).

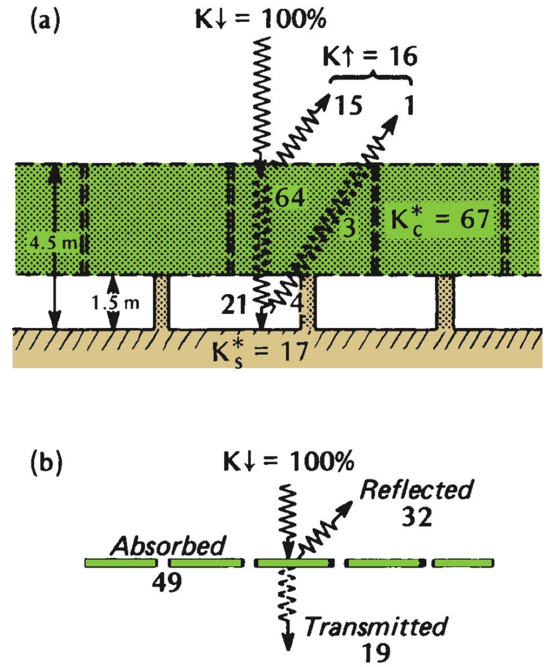

Figure 4: Short-wave radiation budget of (a) an orange orchard, and (b) a single-layer mosaic of fresh orange leaves. All values expressed as percentages of the incident radiation (after Kalma, 1970).

Forest albedos are low by comparison with most other natural vegetation. They are lowest for conifers (especially spruce), higher for bare deciduous and greatest for deciduous trees in full leaf. Since the spectral reflectivity of coniferous needles and deciduous leaves is similar to that of plants, the low albedos are probably due to greater trapping. This is illustrated by the results from an orange orchard given in Figure 4. For a single layer of orange leaves 32% is reflected, 19% transmitted and 49% absorbed, but for the orchard canopy only 15% is reflected, 21% transmitted and 64% absorbed. Hence the natural orientation of leaves and the depth of the canopy greatly enhance absorption due to trapping as a result of multiple internal reflection. On a much smaller scale, enhanced scattering may explain why the diurnal albedo variation of coniferous trees is reduced in comparison with deciduous trees and low plant covers 3. Even at low solar altitudes the roughness of needle clusters may be sufficient to increase scattering and thereby to trap radiation more efficiently than the 'smoother' surfaces of other vegetation covers.

The high absorptivity of evergreen trees makes them extremely important in the radiation budget of a high latitude landscape, especially in the spring in areas where conifers are scattered through otherwise snow-covered terrain with a high albedo. This contrast is accented at low solar altitudes because then the trees present their maximum surface area for irradiation, and their receiving surfaces are almost normal to the solar beam. Their relative warmth makes them sources of longwave radiation which is readily absorbed by the surrounding snow thus hastening the local melt and the exposure of surfaces with lower albedos (see upcoming Lectures).

Additional Readings (not required).

Arya, S.P. (2001): 'Introduction to Micrometeorology', Academic Press, New York, 2nd Ed. Chapter 3.2 (p. 32 - 35)