Chapter 2 | Energy Budget Near the Surface

2.1 Energy Fluxes at an Ideal Surface

The flux of a property in a given direction is defined as its amount per unit time passing through a unit area normal to that direction. In this chapter, we will be concerned with fluxes of the various forms of heat energy at or near the surface. The SI units of energy flux are J s^{-1} m^{-2} or W m^{-2}.

The 'ideal' surface considered here is relatively smooth, horizontal, homogeneous, extensive, and opaque to radiation. The energy budget of such a surface is considerably simplified in that only the vertical fluxes of energy need to be considered.

There are essentially four types of energy fluxes at an ideal surface, namely, the net radiation to or from the surface, the sensible (direct) and latent (indirect) heat fluxes to or from the atmosphere, and the heat flux into or out of the submedium (soil or water). The net radiative flux is a result of the radiation balance at the surface, which will be discussed in more detail in Chapter 3. During the daytime, it is usually dominated by the solar radiation and is almost always directed toward the surface, while at night the net radiation is much weaker and directed away from the surface. As a result, the surface warms up during the daytime, while it cools during the evening and night hours, especially under clear sky and undisturbed weather conditions.

The direct or sensible heat flux at and above the surface arises as a result of the difference in the temperatures of the surface and the air above. Actually, the temperature in the atmospheric surface layer varies continuously with height, with the magnitude of the vertical temperature gradient usually decreasing with height. In the immediate vicinity of the interface and within the so-called molecular sublayer, the primary mode of heat transfer in air is conduction, similar to that in solids. At distances beyond a few millimeters (the thickness of the molecular sublayer) from the interface, however, the primary mode of heat exchange becomes advection or convection involving air motions. The sensible heat flux is usually directed away from the surface during the daytime hours, when the surface is warmer than the air above, and vice versa during the evening and nighttime periods. Thus, the heat flux is down the average temperature gradient.

The latent heat or water vapor flux is a result of evaporation, evapotranspiration, or condensation at the surface and is given by the product of the latent heat of evaporation or condensation and the rate of evaporation or condensation. Evaporation occurs from water surfaces as well as from moist soil and vegetative surfaces, whenever the air above is drier, i.e., it has lower specific humidity than the air in the immediate vicinity of the surface and its transpirating elements (e.g., leaves). This is usually the situation during the daytime. On the other hand, condensation in the form of dew may occur on relatively colder surfaces at nighttime. The water vapor transfer through air does not involve any real heat exchange, except where phase changes between liquid water and vapor actually take place. Nevertheless, evaporation results in some cooling of the surface, which in the surface energy budget is represented by the latent heat flux from the surface to the air above. The ratio of the sensible heat flux to the latent heat flux is called the Bowen ratio.

The heat exchange through the ground medium is primarily due to conduction if the medium is soil, rock, or concrete. Through water, however, heat is transferred in the same way as it is through air, first by conduction in the top few millimeters (molecular sublayer) from the surface and then by advection or convection in the deeper layers (surface layer, mixed layer, etc.) of water in motion. The depth of the submedium, which responds to and is affected by changes in the energy fluxes at the surface on a diurnal basis, is typically less than a meter for land surfaces and several tens of meters for lakes and oceans.

2.2 Energy Balance Equations

2.2.1 The surface energy budget

For deriving a simplified equation for the energy balance at an ideal surface, we assume the surface to be a very thin interface between the two media (air and soil or water), having no mass and heat capacity. The energy fluxes would flow in and out of such a surface without any loss or gain due to the surface. Then, the principle of the conservation of energy at the surface can be expressed as

$$R_N = H + H_L + H_G \tag{2.1}$$

where R_N is the net radiation, H and H_L are the sensible and latent heat fluxes to or from the air, and H_G is the ground heat flux to or from the submedium. Here we use the sign convention that all the radiative fluxes directed toward the surface are positive, while other (nonradiative) energy fluxes directed away from the surface are positive and vice versa.

Equation (2.1) describes how the net radiation at the surface must be balanced by a combination of the sensible and latent heat fluxes to the air and the heat flux to the subsurface medium. During the daytime, the surface receives radiative energy ($R_N > 0$), which is partitioned into sensible and latent heat fluxes to the atmosphere and the heat flux to the submedium. Typically, H, H_L, and H_G are all positive over land surfaces during the day. This situation is schematically shown in Figure 2.1a. Actual magnitudes of the various components of the surface energy budget depend on many factors, such as the type of surface and its characteristics (soil moisture, texture, vegetation, etc.), geographical location, month or season, time of day, and weather. Under special circumstances, e.g., when irrigating a field, H and/or H_G may become negative and the latent heat flux due to evaporative cooling of the surface may exceed the net radiation received at the surface.

At night, the surface loses energy by outgoing radiation, especially during clear or partially overcast conditions. This loss is compensated by gains of heat from air and soil media and, at times, from the latent heat of condensation released during the process of dew formation. Thus, according to our sign

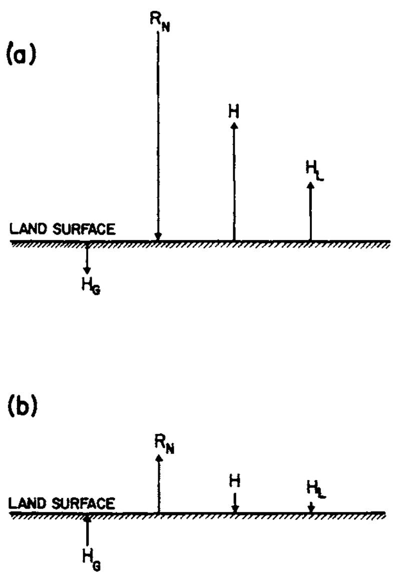

Figure 2.1 Schematic representation of typical surface energy budgets during (a) daytime and (b) nighttime.

convention, all the terms of the surface energy balance [Equation (2.1)] for land surfaces are usually negative during the evening and nighttime periods. Their magnitudes are generally much smaller than the magnitudes of the daytime fluxes, except for H_G. The magnitudes of H_G do not differ widely between day and night, although the direction or sign obviously reverses during the morning and evening transition periods, when other fluxes are also changing their signs (this does not happen simultaneously for all the fluxes, however). Figure 2.1b gives a schematic representation of the surface energy balance during the nighttime.

From the above description of the diurnal cycle of the surface energy budget, it is clear that the fluxes of sensible and latent heat to or from the surface are governed by the diurnal cycle of net radiation. One can interpret Equation (2.1) in terms of the partitioning of net radiation into other fluxes (H, H_L, and H_G). The net radiation may be considered an external forcing, while the sensible, latent and ground heat fluxes are responses to this radiative forcing. Relative measures of this partitioning are the ratios H/R_N, H_L/R_N, and H_G/R_N, which are expected to depend on the various surface, subsurface and meteorological characteristics. Diurnal variations of these ratios are expected to be much smaller than those of the individual fluxes. Of these, the ratio H_G/R_N might be expected to show the least variability, especially for a given land surface, because the above ratio may not be as sensitive to the variations in surface meteorological parameters as H/R_N and H_L/R_N. In simpler parameterizations of the ground heat flux, H_G is assumed to be proportional to R_N or related to R_N through an empirical regression relationship (Doll *et al.*, 1985). The ratio H_G/R_N is found to be larger for nighttime ($R_N < 0$) than for the daytime ($R_N > 0$) conditions. Values exceeding one have been observed during nighttime over urban surfaces, because of positive (upward) sensible heat fluxes even during nighttime.

The simple relationship between the ground heat flux and net radiation allows for the sum of the sensible and latent heat fluxes ($H + H_L$) to be easily determined from the measurement or calculation of net radiation. Further separation of the total heat flux into sensible and latent components can be made if the Bowen ratio, $B = H/H_L$, can be estimated independently (e.g., using the Bowen ratio method to be discussed later). In terms of the Bowen ratio, one can obtain from Equation (2.1)

$$H = \frac{R_N - H_G}{1 + B^{-1}} \tag{2.2}$$

$$H_L = \frac{R_N - H_G}{1 + B} \tag{2.3}$$

The latent heat flux can also be expressed as $H_L = L_e E$, where $L_e \simeq 2.45 \times 10^6$ J kg^{-1} is the latent heat of evaporation/condensation and E is the rate of evaporation/condensation.

Example Problem 1

The average values of the ratio of ground heat flux to net radiation determined from the Wangara experiment data are 0.30 and 0.52 for the daytime and nighttime, respectively. Assuming a Bowen ratio of 5.0, estimate the sensible and latent heat fluxes at that site when the measured net radiation is (a) 250 W m^{-2}, and (b) -55 W m^{-2}.

Solution

(a) $R_N = 250$ W m^{-2}; $H_G = 0.30 \times 250 = 75$ W m^{-2}.
From Equations (2.2) and (2.3), $H = 145.8$ W m^{-2}; $H_L = 29.2$ W m^{-2}.
Check that the above values satisfy Equation (2.1).

(b) $R_N = -55$ W m^{-2}; $H_G = -0.52 \times 55 = -28.6$ W m^{-2}.
From Equations (2.2) and (2.3), $H = -22.0$ W m^{-2}; $H_L = -4.4$ W m^{-2}.
Again, one can check that these values satisfy Equation (2.1).

The energy budgets of extensive water surfaces (large lakes, seas, and oceans) differ from those of land surfaces in several important ways. In the former, the combined value of H_L and H_G balances most of the net radiation, while H plays only a minor role ($H \ll H_L$, or $B \ll 1$). Since the water surface temperature does not respond readily to solar heating due to the large heat capacity and depth of the subsurface mixed layer of a large lake or ocean, the air–water exchanges (H and H_L) do not undergo large diurnal variations.

An important factor to be considered in the energy balance over water surfaces is the penetration of solar radiation to depths of tens of meters. Radiation processes occurring within large bodies of water are not well understood. The radiative fluxes on both sides of the air–water interface must be measured in order to determine the net radiation at the surface. This is not easy to do in the field. Therefore, the surface energy budget as expressed by Equation (2.1) may not be very useful or even appropriate to consider over water surfaces. A better alternative is to consider the energy budget of the whole energy-active water layer.

2.2.2 Energy budget of a layer

An 'ideal,' horizontally homogeneous, plane surface, which is also opaque to radiation, is rarely encountered in practice. More often, the earth's surface has horizontal inhomogeneities at small scale (e.g., plants, trees, houses, and building blocks), mesoscale (e.g., urban–rural differences, coastlines, hills, and valleys), and large scale (e.g., large mountain ranges). It may be partially transparent to radiation (e.g., water, tall grass, and crops). The surface may be sloping or undulating. In many practical situations, it will be more appropriate to consider the energy budget of a finite interfacial layer, which may include the small-scale surface inhomogeneities and/or the upper part of the subsurface medium which might be active in radiative exchanges. This layer must have finite mass and heat capacity which would allow the energy to be stored in or released from the layer over a given time interval. Such changes in the energy storage with time must, then, be considered in the energy budget for the layer.

If the surface is relatively flat and homogeneous, so that the interfacial layer can be considered to be bounded by horizontal planes at the top and the bottom, one can still use a simplified one-dimensional energy budget for the layer:

$$R_N = H + H_L + H_G + \Delta H_S \tag{2.4}$$

where ΔH_S is the change in the energy storage per unit time, per unit horizontal area, over the whole depth of the layer. Thus, the main difference in the energy budget of an interfacial layer from that of an ideal surface is the presence of the rate of energy storage term ΔH_S in the former. Strictly speaking, the various energy fluxes in Equation (2.4), except for ΔH_S, are net vertical fluxes going in or out of the top and bottom faces of the layer. In reality, however, H and H_L are associated only with the top surface (for an interfacial layer involving the water medium, the bottom boundary may be chosen so that there is no significant radiative flux in or out of the bottom surface), as shown schematically in Figure 2.2a.

The rate of heat energy storage in the layer can be expressed as

$$\Delta H_S = \int \frac{\partial}{\partial t}(\rho c T)\, dz \tag{2.5}$$

in which ρ is the mass density, c is the specific heat, T is the absolute temperature of the material at some level z, and the integral is over the whole depth of the layer. When the heat capacity of the medium can be assumed to be constant, independent of z, Equation (2.5) gives a direct relationship between the rate of energy storage and the rate of warming or cooling of the layer.

The energy storage term ΔH_S in Equation (2.4) may also be interpreted as the difference between the energy coming in (H_{in}) and the energy going out (H_{out}) of the layer, where H_{in} and H_{out} represent appropriate combinations of R_N, H, H_L, and H_G, depending on their signs (Oke, 1987, Chapter 2). When the energy input to the layer exceeds the outgoing energy, there is a flux convergence

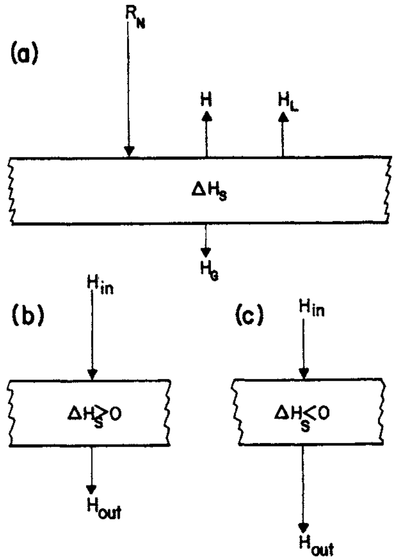

Figure 2.2 Schematic representation of (a) energy budget of a layer, (b) flux convergence, and (c) flux divergence.

($\Delta H_S > 0$) which results in the warming of the layer. On the other hand, when energy going out exceeds that coming in, the layer cools as a result of flux divergence ($\Delta H_S < 0$). In the special circumstances of energy coming in exactly balancing the energy going out, there is no change in the energy storage of the layer ($\Delta H_S = 0$) or its temperature with time. These processes of vertical flux convergence and divergence are schematically shown in Figure 2.2b and c.

Example Problem 2

Over the tropical oceans the Bowen ratio is typically 0.1. Estimate the sensible and latent heat fluxes, as well as the rate of evaporation, in millimeters per day, from the ocean surface, when the net radiation received just above the surface is 400 W m^{-2}, the heat flux to water below 50 m is negligible, the rate of warming of the 50-m-deep oceanic mixed layer is 0.05°C day^{-1}, and the ocean surface temperature is 30°C.

Solution

Here, $R_N = 400$ W m^{-2}; $B = H/H_L = 0.1$.
From Equation (2.5),

$$\Delta H_s = \rho c \int_0^D \frac{\partial T}{\partial t} dz = \rho c D \left(\frac{\partial T}{\partial z}\right)_m$$

where $D = 50$ m is the mixed layer depth, and $(\partial T/\partial z)_m = 0.05°\text{C day}^{-1}$ is the mean (layer-averaged) rate of warming of the mixed layer. Thus,

$$\Delta H_S = 1000 \text{ kg m}^{-3} . 4.18 \times 10^3 \text{ J kg}^{-1} \text{ K}^{-1} . 50 \text{ m} . \frac{0.05}{86\,400} \text{ K s}^{-1} = 121 \text{ W m}^{-2}$$

Substituting in the energy budget Equation (2.4), one obtains

$$H + H_L = 259.1 \text{ W m}^{-2}$$

With the Bowen ratio $H/H_L = 0.1$, one obtains $H = 25.4 \text{ W m}^{-2}$, and $H_L = 253.7 \text{ W m}^{-2}$.
The rate of evaporation,

$$E = H_L/L_e = \frac{253.7 \text{ W m}^{-2}}{2.45 \times 10^6 \text{ J kg}^{-1}}$$
$$= 1.03 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$$

The evaporation rate in terms of the height of water column per unit time = $E/\rho_w = 8.9 \text{ mm day}^{-1}$.

2.2.3 Energy budget of a control volume

In the energy budgets of an extensive horizontal surface and interfacial layer, only the vertical fluxes of energy are involved. When the surface under consideration is not flat and horizontal or when there are significant changes (advections) of energy fluxes in the horizontal, then it would be more appropriate to consider the energy budget of a control volume. In principle, this is similar to the energy budget of a layer, but now one must consider the various energy fluxes integrated or averaged over the bounding surface of the control volume. The energy budget equation for a control volume can be expressed as

$$\bar{R}_N = \bar{H} + \bar{H}_L + \bar{H}_G + \Delta H_S \tag{2.6}$$

where the overbar over a flux quantity denotes its average value over the entire area (A) of the bounding surface and the rate of storage is given by

$$\Delta H_S = \frac{1}{A} \int \frac{\partial}{\partial t} (\rho c T) \, dV \tag{2.7}$$

in which the integration is over the control volume V.

In practice, detailed measurements of energy fluxes are rarely available in order to evaluate their net contributions to the energy budget of a large irregular volume. Still, with certain simplifying assumptions, such energy budgets have been used in the context of several large field experiments over the oceans, such as the 1969 Barbados Oceanographic and Meteorological Experiment (BOMEX) and the 1975 Air Mass Transformation Experiment (AMTEX).

The concept of flux convergence or divergence and its relation to warming or cooling of the medium is more general than depicted in Figure 2.2 for a horizontal layer. For a control volume, the direction of flux is unimportant. According to Equation (2.6), the net convergence or divergence of energy fluxes in all directions determines the rate of energy storage and, hence, the rate of warming or cooling of the medium in the control volume (see Oke, 1987, Chapter 2).

2.3 Energy Budgets of Bare Surfaces

A few cases of observed energy budgets will be discussed here for illustrative purposes only. It should be pointed out that relative magnitudes of the various terms in the energy budget may differ considerably for other places, times, and weather conditions.

Measured energy fluxes over a dry lake bed (desert) on a hot summer day are shown in Figure 2.3. This represents the simplest case of energy balance [Equation (2.1)] for a flat, dry, and bare surface in the absence of any evaporation or condensation ($H_L = 0$). It is also an example of thermally extreme climatic environment; the observed maximum difference in the temperatures between the surface and the air at 2 m was about 28°C.

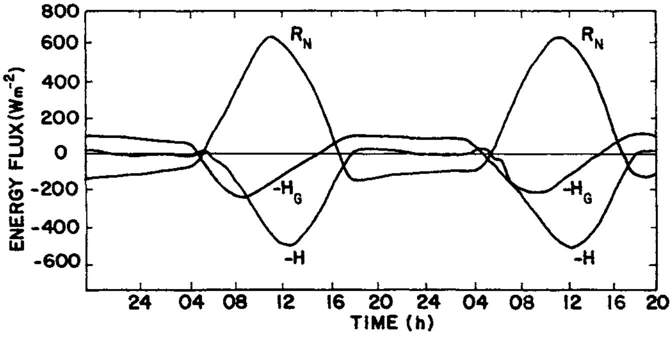

Figure 2.3 Observed diurnal energy budget over a dry lake bed at El Mirage, California, on June 10–11, 1950. [After Vehrencamp (1953).]

Over a bare, dry ground the net radiation is entirely balanced by direct heat exchanges with the surface by both the air and soil media. However, the relative magnitudes of these fluxes may change considerably from day to night, as indicated by measurements in Figure 2.3.

Wetting of the subsurface soil by precipitation or artificial irrigation can dramatically alter the surface energy balance, as well as the microclimate near the surface. The daytime net radiation for the same latitude, season, and weather conditions becomes larger for the wet surface, because of the reduced albedo (reflectivity) and increased absorption of shortwave radiation by the surface. The latent heat flux (H_L) becomes an important or even dominant component of the surface energy balance [Equation (2.1)], while the sensible heat flux to air (H) is considerably reduced. The latter may even become negative during early periods of irrigation, particularly for small areas, due to advective effects. This is called the 'oasis effect' because it is similar to that of warm dry air blowing over a cool moist oasis. There is strong evaporation from the moist surface, resulting in cooling of the surface (due to latent heat transfer). The surface cooling causes a downward sensible heat flux from the warm air to the cool ground. Thus, H_L is positive, while H becomes negative, although much smaller in magnitude. The ground heat flux may also be considerably reduced and even change sign if the surface is cooler than the soil below. Under such conditions, the latent heat flux can be greater than the net radiation. The 'oasis effect' of irrigation disappears as irrigation is applied over large areas and horizontal advections become less important. At later times, the relative importance of H and H_L will depend on the soil moisture content and soil temperature at the surface. As the soil dries up, evaporation rate (E) and $H_L = L_e E$ decrease, while the daytime surface temperature and the sensible heat flux increase with time, for the same environmental conditions. Thus, the daytime Bowen ratio is expected to increase with time after precipitation or irrigation.

A comparison of the surface energy budgets in a dry desert and an irrigated oasis has been given by Budyko (1958). The maximum daytime net radiation in the oasis is 40% larger than that in the dry desert and nearly all of the radiative input to the oasis goes into the latent heat of evaporation. Much smaller positive ground heat flux is nearly balanced by the negative sensible heat flux from air.

2.4 Energy Budgets of Canopies

2.4.1 Vegetation canopies

The growth of vegetation over an otherwise flat surface introduces several complications into the energy balance. First, the ground surface is no longer the most appropriate datum for the surface energy balance, because the radiative, sensible, and latent heat fluxes are all spatially variable within the vegetative canopy. The energy budget of the whole canopy layer [Equation (2.4)] will be more appropriate to consider. For this, measurements of R_N, H, and H_L are needed at the top of the canopy (preferably, well above the tops of plants or trees where horizontal variations of fluxes may be neglected).

Second, the rate of energy storage (ΔH_S) consists of two parts, namely, the rate of physical heat storage and the rate of biochemical heat storage as a result of photosynthesis and carbon dioxide exchange. The latter may not be important on time scales of a few hours to a day, commonly used in micrometeorology. Nevertheless, the rate of heat storage by a vegetative canopy is not easy to measure or calculate.

Third, the latent heat exchange occurs not only due to evaporation or condensation at the surface, but to a large extent due to transpiration from the plant leaves. The combination of evaporation and transpiration is called evapotranspiration; it produces nearly a constant flux of water vapor above the canopy layer.

An example of the observed energy budget over a barley field on a summer day in England is shown in Figure 2.4. Note that the latent heat flux due to evapotranspiration is the dominant energy component, which approximately balances the net radiation, while H and H_G are an order of magnitude smaller. In the late afternoon and evening, H_L even exceeded the net radiation and H became negative (downward heat flux). The rate of heat storage was not measured, but is estimated (from energy balance) to be small in this case.

Forest canopies have similar features to plant canopies, aside from the obvious differences in their sizes and stand architectures. Much larger heights of trees and the associated biomass of the forest canopy suggest that the rate of heat storage may not be insignificant, even over short periods of the order of a day.

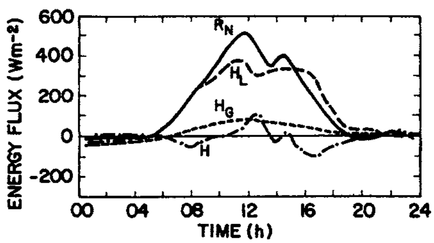

Figure 2.4 Observed diurnal energy budget of a barley field at Rothamsted, England, on July 23, 1963. [From Oke (1987); after Long *et al.* (1964).]

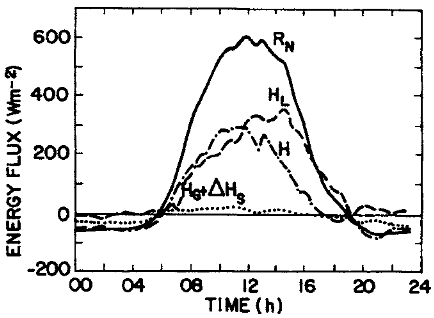

Figure 2.5 Observed energy budget of a Douglas fir canopy at Haney, British Columbia, on July 23, 1970. [From Oke (1987); after McNaughton and Black (1973).]

A typical example of the observed energy budget of a Douglas fir canopy is given in Figure 2.5. In this case, ΔH_S was roughly determined from the estimates of biomass and heat capacity of the trees and measurements of air temperatures within the canopy and, then, added to the measured ground heat flux to get the combined $H_G + \Delta H_S$ term. This term is relatively small during the daytime, but of the same order of magnitude as the net radiation (R_N) at night. Note that, during daytime, R_N is more or less equally partitioned between the sensible and latent heat fluxes to the air. For other examples of measured energy budgets over forests, the reader may refer to Chapter 17 of Munn (1966).

2.4.2 Urban canopies

Urban canopies are much more complex than vegetation canopies, because they represent the large diversity of size, shape, composition, and arrangement of the canopy or 'roughness' elements including buildings, streets, trees, lawns and parks. A useful approach in describing an urban energy budget is to consider a near-surface active layer (urban canopy) or volume (box), whose top is set at or above roof level, and its base at the depth of zero net ground heat flux over the chosen time scale or period (Oke, 1988). Then, one can neglect the extremely complex spatial arrangement of individual canopy elements as energy sources and sinks. The volume or box formulation restricts all energy fluxes, such as R_N, H and H_L, through its top. The internal heat storage change associated with all the canopy elements, the surrounding air and the ground, and internal heat sources due to fuel combustion can be represented as equivalent fluxes through unit area of the top of the box. Thus, an appropriate energy balance for the urban canopy can be expressed as (Oke, 1987, Chapter 8)

$$R_N + H_F = H + H_L + \Delta H_S \tag{2.8}$$

in which H_F is the equivalent heat flux associated with fuel consumption within the urban area or its part (city center, suburb, etc.). Here, we have neglected the net advected heat flow through the sides of the box, assuming that the volume under consideration is surrounded by similar land uses.

In spite of the observed differences in turbidity, temperature, albedo, and emissivity between urban and rural surfaces, the net radiations are not found to be significantly different. But, the addition of the anthropogenic heat flux H_F to R_N makes available substantially more total energy flux for partitioning between the other fluxes on the right-hand side of Equation (2.8). The magnitude of H_F in a city depends on its *per capita* energy use and its population density. Its relative importance in the energy budget of an urban canopy is indicated by the ratio H_F/R_N, which has been estimated for a number of cities in different seasons (Oke, 1987, 1988). The largest values are found in densely inhabited cities in middle and high latitudes and the winter season. Annually averaged values of H_F/R_N for large cities vary between 0.2 (Los Angeles) and 3 (Moscow) with a more typical value of 0.35. Thus, the anthropogenic heat flux is a significant component of the energy budget of any large city. For a particular city, H_F also displays large temporal (both seasonal and diurnal) and spatial variations. In all cases, the central business area or city center appears as the primary heat source, although there may be other localized 'hot spots' in industrial areas. This suggests that H_F can, perhaps, be neglected in the energy budgets of suburban residential areas.

The importance of the sensible heat flux to the energy budget of an urban canopy is well recognized. Built-up urban surfaces (e.g., roofs, streets, and highways) have low surface albedos (0.1–0.2) and readily absorb solar radiation during daytime. With their increased temperatures and enhanced turbulence activity in the urban canopy, a large portion of the available energy is transferred to the atmosphere as sensible heat. The impervious nature of these surfaces reduces the surface water availability for evaporation. Consequently, the latent heat flux is relatively small and the Bowen ratio is large. But, locally, the situation is much different over irrigated lawns or green parks. In urban areas, built-up impervious surfaces and natural pervious surfaces constitute two contrasting surface types with widely different energy budgets on a local basis (Oke, 1987, Chapter 8).

The importance of the heat storage term ΔH_S in the urban canopy budget is also recognized. However, it is almost impossible to determine it from direct measurements, considering the many absorbing elements and surfaces involved in an urban canopy. In most experimental studies of energy budget, ΔH_S is determined as the residual term from the energy balance equation. So far, such studies have been confined to suburban areas where measurements can be made with instruments placed on towers and roof tops.

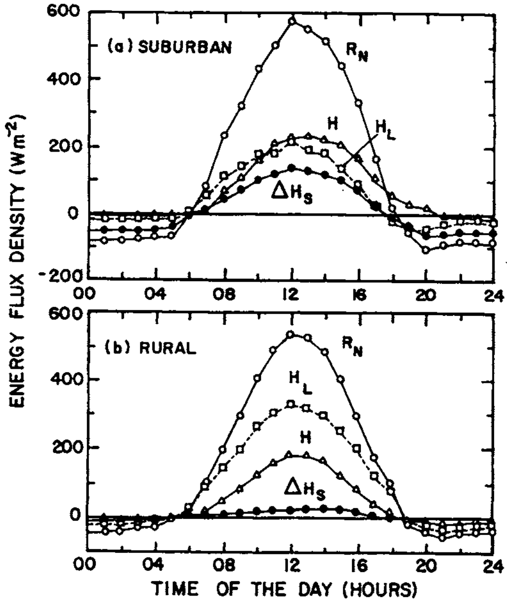

Figure 2.6 Monthly-averaged energy budgets at suburban and rural sites in Greater Vancouver, Canada, during summer. [From Oke (1987).]

An illustration of the suburban energy budget is shown in Figure 2.6 where it is compared with that of a nearby rural surface. The various fluxes shown are monthly averages for suburban and rural sites in Greater Vancouver, Canada, during summer (Oke, 1987, Chapter 8). These are based on direct measurements of R_N and H, calculated ΔH_S, and estimated H_L as the residual in the energy balance equation. The suburban area is an area of fairly uniform one- or two-storey houses (36% built and 64% greenspace), while the 'rural' site is an extensive area of grassland. For the latter, ΔH_S essentially represents H_G. As expected, the heat storage term over the suburban area is a significant part of the energy budget, especially at nighttime. Some day-to-day variations of the energy budget of the same suburban area are shown by Oke (1988). Grimmond and Oke (1995) compare the summertime energy budgets of the suburbs for four North American cities (Chicago, Los Angeles, Sacramento, and Tucson) under clear, cloudy, and all sky conditions. As expected, the magnitudes of fluxes vary between cities; however, the diurnal trends of flux partitioning are similar in terms of the timing of the peaks and changes in sign.

Similar observations of the energy budgets of more heavily built city centers and commercial and industrial districts are lacking. However, we may anticipate both H and ΔH_S playing a much larger role than in the suburbs, and H_L playing a smaller role. Anthropogenic heat flux H_F is expected to be too large to ignore, while the contribution of heat advection to or from surrounding areas may also have to be considered.

2.5 Energy Budgets of Water Surfaces

Water covers more than two-thirds of the earth's surface. Therefore, it is important to understand the energy budget of water surfaces. It is complicated, however, by the fact that water is a fluid with a dynamically active surface and a surface boundary layer or mixed layer in which the motions are generally turbulent. Thus, convective and advective heat transfers within the surface boundary layer in water essentially determine H_G. However, it is not easy to measure these transfers or H_G directly. As discussed earlier, the radiation balance at the water surface is also complicated by the fact that shortwave radiation penetrates to considerable depth in water. Therefore, it will be more appropriate to consider the energy budget of a layer of water extending to a depth where both the convective and radiative heat exchanges become negligible. This will not be feasible, however, for shallow bodies of water with depths less than about 10 m.

Even over large lakes and oceans, simultaneous measurements of all the energy flux terms in Equation (2.4) on a short-term basis are lacking, largely because of the experimental difficulties associated with floating platforms and sea spray. The sensible and latent heat fluxes are the most frequently measured or estimated quantities. Over most ocean areas the latter dominates the former and the Bowen ratio is usually much less than unity (it may approach unity during periods of intense cold air advection over warm waters). The rate of heat storage in the oceanic mixed layer plays an important role in the energy budget. This layer acts as a heat sink ($\Delta H_S > 0$) by day and a heat source ($\Delta H_S < 0$) at night.

The significance of net radiation in the energy budget over water is not so clear. For some measurements of heat balance at sea on a daily basis in the course of a large experiment, the reader may refer to Kondo (1976).

2.6 Applications

The following list includes some of the applications of energy balance at or near the earth's surface.

- Prediction of surface temperature and frost conditions.
- Indirect determination of the surface fluxes of heat (sensible and latent) to or from the atmosphere.

- Estimation of the rate of evaporation from bare ground and water surfaces and evapotranspiration from vegetative surfaces.
- Estimation of the rate of heat storage or loss by an oceanic mixed layer or a vegetative canopy.
- Study of microclimates of the various surfaces.
- Prediction of icing conditions on highways.

In all these and possibly other applications, the various terms in the appropriate energy balance equation, except for the one to be estimated or predicted, have to be measured, calculated, or parameterized in terms of other measured quantities.

Problems and Exercises

1. Describe the typical conditions in which you would expect the Bowen ratio to be as follows:
(a) much less than unity;
(b) much greater than unity;
(c) negative.

2.
(a) Over an ocean surface, the Bowen ratio is estimated to be about 0.2. Estimate the sensible and latent heat fluxes to the atmosphere, as well as the rate of evaporation, in millimeters per day, from the ocean surface, when the net radiation received just above the surface is 600 W m^{-2}, the heat flux to the water below 50 m is negligible, the rate of warming of the 50 m deep oceanic mixed layer is 0.08°C day^{-1}, and the sea surface temperature is 25°C.
(b) What will be the rate of warming or cooling of the 50 m deep oceanic mixed layer at the time of intense cold-air advection when the Bowen ratio is estimated to be 0.5, the net radiation loss from the surface is 50 W m^{-2}, and the rate of evaporation is 20 mm day^{-1}?

3. Giving schematic depictions, briefly discuss the energy balance of an extensive, uniform snowpack for the following conditions:
(a) below-freezing air temperatures;
(b) above-freezing air temperatures.

4.
(a) Give a derivation of Equation (2.5) for the rate of heat storage in a soil layer.
(b) Will the same expression apply to an oceanic mixed layer? Give reasons for your answer.

5. Explain the following terms or concepts used in connection with the energy balance near the surface:
(a) 'ideal' surface;
(b) evaporative cooling;
(c) oasis effect;
(d) flux divergence.

6.
(a) What are the major differences between the energy budgets of a bare soil surface and a vegetative surface?
(b) How would you rewrite the energy balance of a subsurface soil layer and how does it differ from that for the bare soil surface?

7.
(a) Explain the processes and mechanisms involved in the increase of the surface temperature during morning hours after sun rise.
(b) Is the surface energy balance equation (Equation 2.1) valid even when the surface temperature is rising rapidly with time?

8.
(a) Explain the importance of the change in heat storage in the energy budget of an urban canopy.
(b) What are the different elements or components of ΔH_S in Equation (2.8) and why is it so difficult to measure directly?

9.
(a) How would you measure the rate of heat storage in the mixed layer of an ocean?
(b) Discuss the mechanisms or processes involved in the daytime warming of the oceanic mixed layer and qualitatively compare it with that of a subsurface soil layer.