components of Equation (3.10) for a clear August day in England over a thick stand of grass, when the diurnal variation of grass temperature was about 20°C. Note that in this case about one-fourth of the incident solar radiation was reflected back by the surface, while about three-fourths was absorbed. The net radiation is slightly less than $R_s$, even during the midday hours, because of the net loss due to longwave radiation. The diurnal variation of $R_{L1}$ is much less than that of $R_{L1}$ (28% variation in $R_{L1}$ is consistent with the observed diurnal range of 20°C in surface temperature).

Figure 3.5 shows the diurnal variation of radiation budget components over Lake Ontario on a clear day in August. Note that the measured shortwave radiation ($R_{S1}$) near the lake surface is only about two-thirds of the computed solar radiation ($R_0$) at the top of the atmosphere. Of this, 25–30% is in the form of diffuse-beam radiation ($R_D$) at midday and the rest as direct-beam solar radiation (not plotted). The outgoing shortwave radiation ($R_{S1}$) is relatively small, due to the low albedo ($a \approx 0.07$) of water. Both the incoming and outgoing longwave radiation components are relatively constant with time, due to small diurnal variations in the temperatures of the lake surface and the air above it. The net longwave radiation is a constant energy loss throughout the period of observations. The net radiation ($R_N$) is dominated by $R_{S1}$ during the day and is equal to $R_L$ at night.

Figure 3.5 Observed radiation budget over Lake Ontario under clear skies on 28 August 1969. [From Oke (1987); after Davies et al. (1970).]

3.6 Radiative Flux Divergence

The concept of energy flux convergence or divergence and its relation to cooling or warming of a layer of the atmosphere of submedium has been explained in Chapter 1. Here, we discuss the significance of net radiative flux convergence or divergence to warming or cooling in the lowest layer of the atmosphere, namely, the PBL.

The rate of warming or cooling of a layer of air due to change of net radiation with height can be calculated from the principle of conservation of energy. Considering a thin layer between the levels $z$ and $z + \Delta z$, where the net radiative fluxes are $R_N(z)$ and $R_N(z + \Delta z)$, as shown in Figure 3.6, we get

\[ \rho c_p \Delta z (\partial T/\partial t)_R = R_N(z + \Delta z) - R_N(z) = (\partial R_N/\partial z) \Delta z \]

or

\[ (\partial T/\partial z)_R = (1/\rho c_p) (\partial R_N/\partial z) \quad (3.17) \]

where $(\partial T/\partial t)_R$ is the rate of change of temperature due to radiation and $\partial R_N/\partial z$ represents the convergence or divergence of net radiation. Radiative flux convergence occurs when $R_N$ increases with height $(\partial R_N/\partial z > 0)$ and divergence occurs when $\partial R_N/\partial z < 0$. The former leads to warming and the latter to cooling of the air. Warming or cooling of air due to radiative flux convergence or divergence is only a part of the total warming or cooling. Contributions of warm or cold air advection and turbulent exchange of sensible heat will be discussed later in Chapter 5.

In the daytime, during clear skies, net radiation is dominated by the net shortwave radiation ($R_S$), which usually does not vary with height in the PBL.
3 Radiation Balance Near the Surface

- Parameterizing the surface heat fluxes to soil and air in terms of net radiation.
- Determining radiative cooling or warming of the PBL.

These and other applications are particularly important in determining the microclimates of various natural and urban areas.

Problems and Exercises

1. The following measurements were made over a short grass surface on a winter night when no evaporation or condensation occurred:
   - Outgoing longwave radiation from the surface = 365 W m\(^{-2}\).
   - Incoming longwave radiation from the atmosphere = 295 W m\(^{-2}\).
   - Ground heat flux from the soil = 45 W m\(^{-2}\).
   (a) Calculate the apparent (equivalent blackbody) temperature of the surface.
   (b) Calculate the actual surface temperature if surface emissivity is 0.92.
   (c) Estimate the sensible heat flux to or from air.

2. (a) Estimate the combined sensible and latent heat fluxes from the surface to the atmosphere, given the following observations:
   - Incoming shortwave radiation = 800 W m\(^{-2}\).
   - Heat flux to the submedium = 150 W m\(^{-2}\).
   - Albedo of the surface = 0.35.
   (b) What would be the result if the surface albedo were to drop to 0.07 after irrigation?

3. The following measurements or estimates were made of the radiative fluxes over a short grass surface during a clear sunny day:
   - Incoming shortwave radiation = 675 W m\(^{-2}\).
   - Incoming longwave radiation = 390 W m\(^{-2}\).
   - Ground surface temperature = 35°C.
   - Albedo of the surface = 0.20.
   - Emissivity of the surface = 0.92.
   (a) From the radiation balance equation, calculate the net radiation at the surface.
   (b) What would be the net radiation after the surface is thoroughly watered so that its albedo drops to 0.10 and its effective surface temperature reduces to 25°C?
   (c) Qualitatively discuss the effect of watering on other energy fluxes to or from the surface.

4. Show that the variation of about 28% in terrestrial radiation in Figure 3.4 is consistent with the observed range of 10–30°C in surface temperatures.

5. Explain the nature and causes of depletion of the solar radiation in passing through the atmosphere.

6. Discuss the consequences of the absorption of longwave radiation by atmospheric gases and the so-called greenhouse effect.

7. Discuss the merits of the proposition that net radiation \( R_N \) can be deduced from measurements of solar radiation \( R_S \), during the daylight hours, using the empirical expression

   \[
   R_N = AR_S + B
   \]

   where \( A \) and \( B \) are constants. On what factors are \( A \) and \( B \) expected to depend?

8. (a) Discuss the importance and consequences of the radiative flux divergence at night above a grass surface.
   (b) If the net longwave radiation fluxes at 1 and 10 m above the surface are \(-135\) and \(-150\) W m\(^{-2}\), respectively, calculate the rate of cooling or warming in °C h\(^{-1}\) due to radiation alone.

9. The following measurements were made at night from a meteorological tower:
   - Net radiation at the 2 m level = \(-125\) W m\(^{-2}\).
   - Net radiation at the 100 m level = \(-165\) W m\(^{-2}\).
   - Sensible heat flux at the surface = \(-75\) W m\(^{-2}\).
   - Planetary boundary layer height = 80 m.
   Calculate the average rate of cooling in the PBL due to the following:
   (a) the radiative flux divergence;
   (b) the sensible heat flux divergence.
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