GEOG 321 - Reading Package Lecture 3

Oke, T., Mills, G., Christen, A., & Voogt, J. (2017). Urban Climates. Cambridge: Cambridge University Press. doi:10.1017/9781139016476, pages 156-158 (Section 6.1.1)

6 Energy Balance

Figure 6.1 An extreme case of the replacement of natural properties (surface geometry, materials) by built ones (including anthropogenic heat for space cooling) that radically alter the surface water and energy balances. An alley (microscale) in Singapore, which is otherwise renowned for the abundance of vegetation (especially trees), throughout the city (Credit: L. Wee/Getty Images; with permission).

The **surface energy balance** (SEB) is the fundamental starting point if we are to understand and predict surface **microclimates** and climates of the **atmospheric boundary layer** (ABL). It is a statement of the conservation of energy which is applicable to surfaces and volumes at all spatial and temporal scales. It is used here to assess the transfer and storage of energy within an urban system and between that system and the atmosphere. For urban systems, energy balances can be written for individual **facets** (roofs, walls, roads etc.), for urban elements immersed in the urban atmosphere (human body, buildings), for the entire surface-atmosphere interface, or for selected layers of the atmosphere.

Figure 6.1 is an arresting viewpoint from a relatively extreme canyon within an **urban canopy layer** (UCL) in Singapore. The environment is comprised entirely of hard, **impermeable** manufactured materials. The canyon formed by the buildings and road regulates aerodynamic and radiative exchanges with the overlying atmosphere (Chapters 4 and 5). The underlying substrate is sealed so that its water content is not recharged through the surface. Moreover, there is no vegetation so the normal transfer of water from the substrate to the atmosphere via plant roots and stoma cannot occur. These modifications to the **surface cover** are accompanied by the complementary actions of the city's inhabitants. Note the cables and pipes, they are conduits for energy and water supplies to and from the buildings on either side of the street. Whilst there are small openings in the walls that allow ventilation, it is apparent that much of the imported energy is used to create a comfortable indoor climate through air conditioning systems, in what is otherwise a challenging **macroclimate**. However, indoor cooling requires that waste energy is exhausted to the outdoor atmosphere (see the fan-driven exhaust systems on each cooling unit). This image illustrates several of the radical transformations of the SEB that accompanies urban development.

6.1 Basics of Energy Transfer and Balance

6.1.1 Energy Balance of a Flat Surface

In a nutshell, variations in the climate of a surface and of the ABL are driven by the SEB, which describes the net result of energy exchanges (flux densities in W m^{-2}) by **radiation**, **convection** and **conduction** between a facet, an element or a land surface and the atmosphere. Figure 6.2a deals with the simplest case where all heat flux densities are restricted to the vertical — essentially a one-dimensional view at a horizontally extensive grassland site. By selecting an extensive site we avoid complications arising from horizontal heat transport from markedly different upwind surfaces.

The Surface Energy Balance Equation

The relevant flux densities at a non-urban land surface are: the **net allwave radiation** Q^* (see Chapter 5); the ground heat flux density, that transfers **sensible heat** by conduction to the substrate (Q_G); and the two turbulent heat flux densities that exchange energy between the surface and atmosphere – the **sensible heat flux density** Q_H and the **latent heat flux density** Q_E. Energy conservation means those fluxes must balance at a surface:

$$Q^* = Q_H + Q_E + Q_G \qquad (\mathrm{W\ m^{-2}}) \qquad \textbf{Equation 6.1}$$

Notice that Equation 5.1 is a genuine statement of *balance* whereas for radiation (Chapter 5) we referred to the disposition at a surface as a *budget*. In a balance the sum of all terms including their sign is zero at all times, whereas in a budget it is more like a bank account, where it is normal to have a surplus or

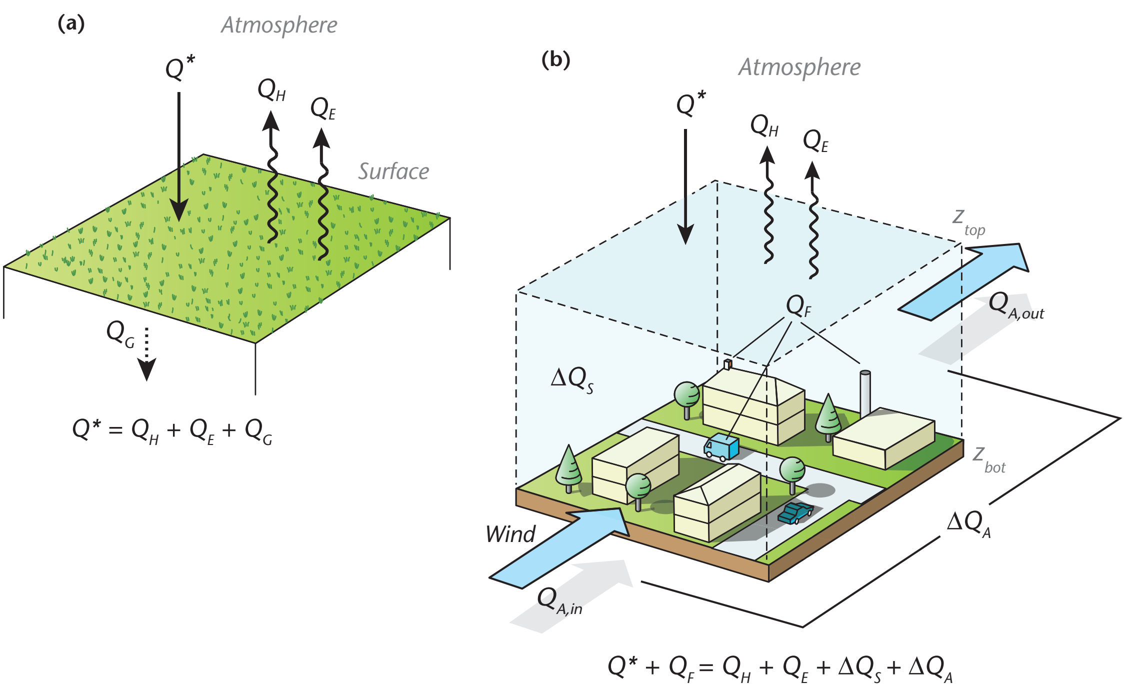

Figure 6.2 Schematic of the fluxes in the SEB of **(a)** a rural and **(b)** an urban building-soil-air volume. The volume that extends from the top of the RSL (z_{top}) down to a depth where there is no net conduction over the period of interest (z_{bot}). Arrows are drawn in the direction the corresponding flux is considered positive. For ΔQ_S and ΔQ_A, they are positive if the internal energy of the volume increases. (Modified after: Oke, 1987).

deficit. That is because radiation is only one form of energy, not a complete statement of the total energy of the system.

Turbulent Heat Flux Densities

Q_H is driven by temperature differences *between* the surface and atmosphere, and minimizes temperature differences *within* the atmosphere by mixing warmer and cooler eddies. Q_E is the consequence of transporting water vapour (a mass **flux density** E of water or **evaporation** in kg m^{-2} s^{-1}) and the associated **latent heat** towards or away from the surface. By latent heat we refer to the energy that was used to vapourize the water mass. Q_E and E are linked:

$$Q_E = \mathcal{L}_v E \qquad (\mathrm{W\ m^{-2}}) \qquad \textbf{Equation 6.2}$$

where $\mathcal{L}_v$ is the latent heat of vapourization (2.464 MJ kg^{-1} at 15°C). Once evaporated, the latent heat remains present in water vapour by virtue of it existing in the higher energy state. It is liberated again during **condensation**, if the vapour condenses back into liquid, for example in the process of cloud droplet formation – this could happen far away from the place of evaporation. **Dewfall** is the reverse process to evaporation, it causes negative Q_E. In dewfall water vapour is transported to a relatively cold surface where it condenses and releases the same amount of latent heat per unit mass as it locked up in the evaporation process. Smaller, but still significant, amounts of heat accompany the processes of melting and freezing, and the two are summed if **sublimation** occurs (e.g. the liquid state is absent in the conversion). Evaporation removes energy from the local environment, causing the surface and near-surface air to cool; condensation returns it and warms the environment. The changes in air and surface temperature are measurable (i.e. it is sensible), but the temperature of the vapour remains unchanged.

The ratio of the two turbulent heat flux densities Q_H/Q_E, known as the **Bowen ratio** (β), is significant to a surface climate. If $\beta > 1$ it indicates that the surface or system channels more heat into sensible form, which warms the lower atmosphere whereas, if $\beta < 1$ latent heat dominates, which keeps the surface and near-surface air cooler, whilst it adds humidity to the environment.

Temporal Evolution of the Surface Energy Balance

The pattern of radiation receipts from the Sun sets the fundamental daily and seasonal rhythms of external energy supply (Chapter 5). Equation 6.1 requires that the daytime radiation surplus at the surface ($Q^* > 0$) is conducted in the form of sensible heat into the soil (Q_G) or convected by **turbulent** transport into the lower atmosphere (Q_H and Q_E). At night all flux densities usually reverse sign. The surface becomes a net emitter of radiation ($Q^* < 0$) and the surface cools, forming a temperature **inversion** in the lowest layer. That heat drain is balanced by the sum of a negative Q_G conducted up from the warmer subsoil, plus negative (and smaller in magnitude) Q_H and Q_E transporting energy from the atmosphere towards the surface. The lowest air layers cool and perhaps dry slightly due to an intermittent flux of vapour onto the colder surface, as dew or frost.

Daytime **turbulent fluxes** and the warming and humidification of the lowest atmosphere, are facilitated by instability that aids mechanical and thermal **turbulence** (Chapter 4), whereas nocturnal stability suppresses convection. There is a phase difference between the daytime course of Q_G compared to those of Q_H and Q_E. Q_G typically peaks an hour or two before Q^*, whereas the timing of the peak of Q_H and Q_E relative to Q^* and relative to each other, is more complex. The phase of the curves depends on the surface properties (e.g. height of roughness elements, thermal properties) and the state of the ABL (e.g. atmospheric dryness, turbulence) (see Section 6.4.1). Similarly, these controls underlie the asymmetric timing of the resulting daily waves of surface, air and soil temperature.

In summary, the SEB determines the near-surface thermal microclimates of a site, which in turn are controlled by the amalgam of its **forcings** (largely set by the state of the ABL) in combination with the unique mix of radiative, aerodynamic, thermal and moisture properties of constituent surfaces.

6.1.2 Energy Balance of Urban Systems and Elements

Urban development of a previously **rural** site leads to significant disturbance of the surface geometry and properties. Natural materials are removed, replaced or modified by a new mix introduced that is often dominated by construction materials. The radiative, aerodynamic, thermal and moisture properties of these materials are radically different to natural ones leading to a greatly modified surface and very different micro- and mesoclimates of the surface and ABL.