5. Energy Balance

Reading Assignment:
- A&B: Ch. 3  (p. 60-69)
- CD: tutorial: energy balance concepts

1. Introduction

- Past section was concerned with radiant energy that was transferred by radiation
  - net result of all radiation processes = net radiation
  - net radiation = amount of energy available for other forms of energy and energy transport
- conversion of radiant energy into heat, where absorption occurs: at the surface
- heat is transported away from the surface (other than by radiation) by (see section Energy Transfer):
  - convection: heat is transported because of the flow or circulation of a fluid (liquids, gases)
  - conduction: heat transported molecule by molecule; in fluids slow compared to convection; only way in solids (ground)
2. The Surface Energy Balance Equation

\[ Q^* = Q_G + Q_H + Q_E \quad \text{W m}^{-2} \]

- \( Q_G \): Soil heat flux \([\text{heat the ground}]\)
- \( Q_H \): Sensible heat flux \([\text{heat the air}]\)
- \( Q_E \): Latent heat flux \([\text{evaporate water}]\)

\( Q^* \): Net all wave radiation

\[ Q^* = (K\downarrow - K\uparrow) + (L\downarrow - L\uparrow) \]

**Sign Convention:**

![Diagram showing the energy fluxes](image)
As in the radiation balance equation, each term in the surface energy balance equation represents an energy transport process.

(i) \( Q_G \) - Soil heat flux = conductive flux

- energy that goes into heating the ground.

\[
Q_G = - k_s \frac{\Delta T}{\Delta d}
\]

\( k_s \): soil heat conductivity
(ii) $Q_H$ - **Sensible Heat Flux** = (turbulent) convective flux

- energy that goes into heating the air
- **Convection** occurs when there is **vertical circulation and mixing** in the atmosphere:
  - air in contact with the surface gains heat
  - rise
  - mixes with cooler air
  - rising air replaced by slowly sinking cooler air from above
(iii) \( Q_E \) - Latent Heat Flux = (turbulent) convective flux

- energy that is used to evaporate water
- Exchange of energy

Without vertical motion:
- air immediately above the surface quickly becomes saturated with water vapor.

Exchange of latent heat is greatest when the air near the surface is continually replaced by drier air above the surface (i.e. under turbulent, windy conditions).
4. Latent Heat of Vaporization ($L_v$)

$L_v :=$ amount of energy (per mass) required to change the phase of a substance from liquid to gaseous

- Depends on type, temperature of the substance

Phase Changes:
- Change of water from: solid $\Rightarrow$ liquid $\Rightarrow$ gas phase
- Change from: gaseous $\Rightarrow$ liquid $\Rightarrow$ solid phase

Energy surplus at the surface can be used to:
- melt ice, evaporate liquid water or sublimate ice.
  - *Melting*: $\Rightarrow$ no temperature change occurs (Lab 3).
  - *Vaporization and sublimation*: energy is stored as latent heat

$$Q_E \iff \rho v E \iff Q_E = \rho v E L_v$$

Latent Heat flux $\iff$ Vapor flux
Global Energy Balance

see Tutorial on CD

Space:
-5 -25 +100 -66 -4 = 0

Atmosphere:
+25 -66 +100 +22 +7 = 0

Surface:
+45 +88 -104 -22 -7 = 0

(a) ANNUAL RADIATION BUDGET

Incoming radiation
Outgoing radiation
Surplus
Deficit

Energy (Watts per square meter)

LATITUDE (Degrees)

85 65 45 25 5 5 25 45 65 85

Southern Hemisphere Northern Hemisphere
5. Water Balance

- MASS, LIKE ENERGY, IS CONSERVED

\[
p = E + \Delta r + \Delta S \quad \text{mm h}^{-1} (\equiv 10^{-3} \text{ m h}^{-1})
\]

- \(p\) precipitation
  - rainfall, snow etc.
- \(E\) evapotranspiration
  - Energy equivalent is \(Q_E\)
- \(\Delta r\) net runoff
  - e.g. river
- \(\Delta S\) net storage change
  - e.g. soil moisture, change in lake level

**Summary:**

The Energy Balance Equation:

\[
Q^* = Q_G + Q_H + Q_E
\]

The Water Balance Equation:

\[
p = \Delta r + \Delta S + E
\]
Global Water Cycle

- Evaporation surplus over ocean
- Condensation/Precipitation surplus over land

= global air conditioner / heat pump
6. The Bowen Ratio ($\beta$)

$\beta := \text{Ratio of the two convective fluxes } Q_H \text{ and } Q_E$

$$\beta = \frac{Q_H}{Q_E}$$

Indicates partitioning of energy:
- to heat the air
- to evaporate water (consume liquid water)

• $Q_H > Q_E$ $\beta > 1$ dry surface
  
  E.g. desert $\beta \approx 10$
  urban area $\beta \approx 2$

• $Q_H < Q_E$ $\beta < 1$ wet surface
  
  Agriculture (irrigated) $\beta \approx 0.25$
  Forest (not irrigated) $\beta \approx 0.8$