ETH
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Radiation, sensible heat flux and evapotranspiration

Climatological and hydrological field work

1 The surface radiation and energy balance

Solar radiation is the primary energy source for the climate system. At the Earth surface (Figure 1), the net radiative flux represents the energy that is available for

1. heating or cooling the soil
2. changing the phase of water present at the surface through evaporation, condensation, melting, freezing or sublimation
3. heating or cooling air in the boundary layer, eventually inducing convection or subsidence.

The net radiation at the surface is thus both important for the thermal structure as well as for the dynamics of the atmosphere and the water cycle.

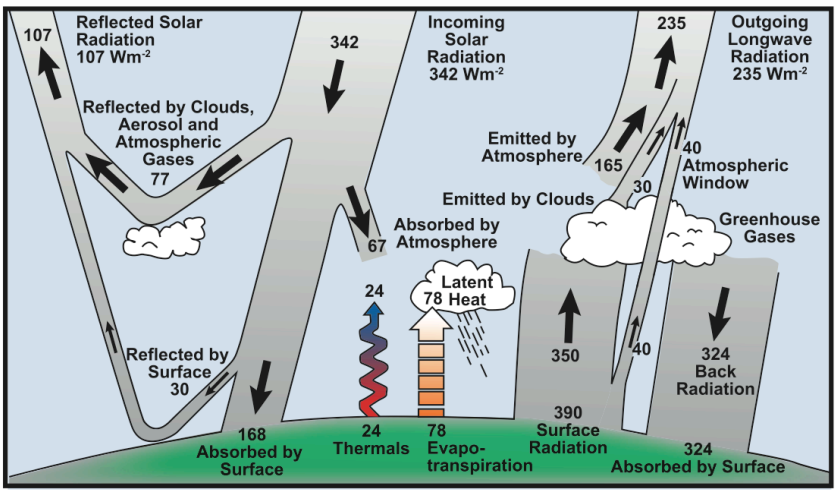

Figure 1: Estimate of the Earth's annual global mean energy balance. Over the long term, the incoming solar radiation absorbed by the Earth and the atmosphere is balanced by the longwave radiation emitted by the two. About half of the incoming solar radiation is absorbed by the surface. This energy is transferred to the atmosphere by warming the near-surface air (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere radiates longwave energy back to the surface and out to space. Source: Kiehl & Trenberth (1997).

1.1 Radiation at the surface

The net radiation at the surface is the result of a combination of different radiative processes. The incident shortwave radiation is reflected (mainly by clouds) and absorbed (mainly by oxygen, ozone and water vapor). At the surface, the incoming global shortwave radiation (shortwave downward radiation $SW_{\downarrow}$, Wm^{-2}) consists of a direct and a diffuse component. Part of the the incoming radiation is reflected at the surface (shortwave upward radiation $SW_{\uparrow}$, Wm^{-2}). The fraction of reflected radiation is determined by the surface albedo α, which depends on optical properties of the surface. The amount of longwave radiation emitted at the surface (longwave upward radiation $LW_{\uparrow}$, Wm^{-2}) depends on the radiative temperature T_r (K) and the emissivity ϵ, of which the latter describes how close the Earth is to a black body. According to Planck's law, every body at a certain temperature T_r (K) emits longwave radiation amounting to $\epsilon\sigma T_r^4$, where σ is the Stephan Bolzmann constant ($5.67 \cdot 10^{-8}$ W K^{-4} m^{-2}). In the atmosphere, this thermal radiation is absorbed mainly by water vapor and other greenhouse gases and re-emitted both upwards and downward toward the surface (longwave downward radiation, $LW_{\downarrow}$, Wm^{-2}). The longwave downward radiation depends on the atmospheric temperature and water vapor distribution, and cloud cover. At the surface, $RLW_{\downarrow}$ is reflected again, assuming the Earth to be a grey body (for which its reflectivity $R = 1 - \epsilon$; "a good emitter is a good absorber, i.e., a bad reflector"). As Earth is a good absorber with high ϵ, its reflectivity is typically very small and will be neglected here.

$$R_n = SW_{\downarrow} - SW_{\uparrow} + LW_{\downarrow} - LW_{\uparrow} \quad (1)$$

$$SW_{\uparrow} = \alpha SW_{\downarrow} \quad (2)$$

$$LW_{\uparrow} = \epsilon\sigma T_r^4. \quad (3)$$

The four components of the upward and downward, solar and thermal radiation, add up to the surface net radiation (net radiation R_n, Wm^{-2}; see Equation 1). Equations

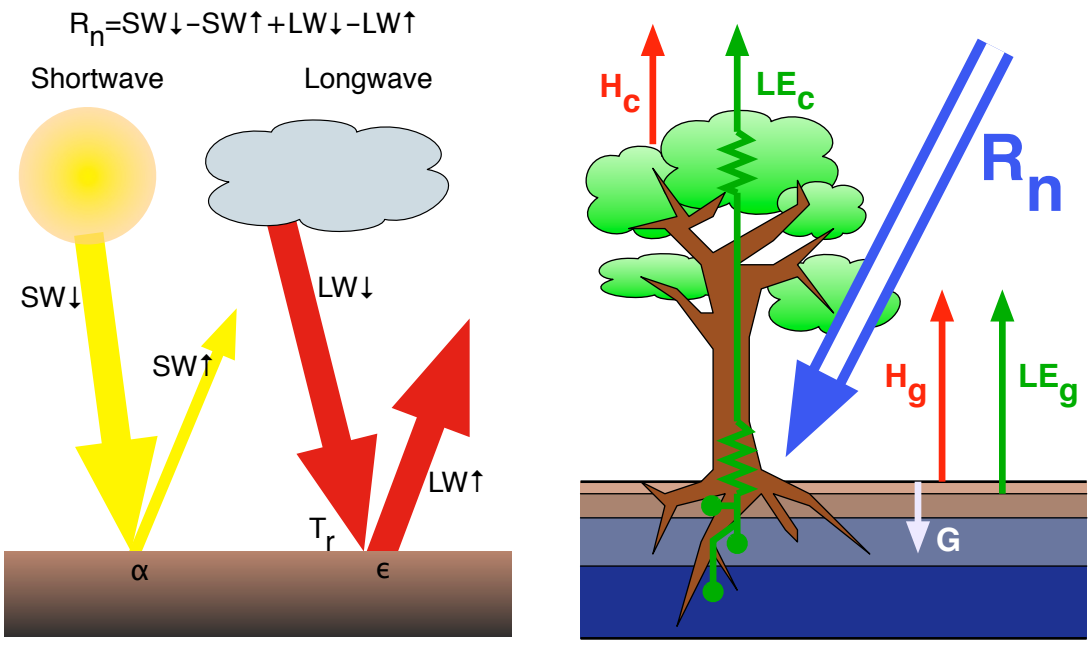

Figure 2: Radiation balance (left) and energy balance (right) at the Earth surface.

2 and 3 show the relationship between reflected shortwave radiation and albedo as well as the longwave upward radiation and the emissivity and the radiative temperature.

1.2 Energy fluxes at the surface

At the surface net radiation R_n is partitioned into the sensible heat flux H, the latent heat flux λE and the ground heat flux G through the energy balance (Equation 4).

$$R_n = H + \lambda E + G. \tag{4}$$

E is also called evapotranspiration and $\lambda = 2.5 \cdot 10^6\,\mathrm{J\,kg^{-1}}$ is the latent heat of evaporation of water. Evapotranspiration thus links the radiation (Equation 4) to the water balance (Equation 5), also shown in Figure 2.

$$\frac{dS}{dt} = P - E - Q, \tag{5}$$

Equation 5 relates evapotranspiration E to changes in terrestrial water storage (dS/dt), precipitation P and runoff Q. In a first order approximation the sensible heat flux and evapotranspiration can be expressed as

$$H = c_p \rho K_h \frac{\Delta T}{\Delta z} \tag{6}$$

$$E = \rho K_E \frac{\Delta q}{\Delta z}, \tag{7}$$

where ρ is the air density, c_p the specific heat of air, $\Delta q/\Delta z$ is the change of specific humidity and $\Delta T/\Delta z$ is the change of air temperature with height, i.e., the respective vertical gradients near the surface. The transfer coefficients (K_H, K_E) summarize the combined effects of processes such as atmospheric turbulence or vegetation activity and are difficult to estimate. The relation between the latent and the sensible heat flux can be described using the Bowen ratio, which is specified as:

$$Bo = \frac{H}{\lambda E} = \frac{c_p \Delta T}{\lambda \Delta q} = \gamma \frac{\Delta T}{\Delta e}, \tag{8}$$

assuming that the transfer coefficients in Equation 6 and Equation 7 are approximately equal ($K_H \approx K_E$). Here ΔT and Δq are the difference in temperature and specific humidity at two elevations. Δe is the difference in vapor pressure and $\gamma \approx 0.67$ hPa / K is the psychrometric constant. Finally, the Bowen ration can be combined with the energy balance equation (4) to derive estimates of the sensible and latent heat flux. Under the assumption that the ground heat flux is often negligible ($G \ll H + \lambda E$) the fluxes are specified as:

$$H = \frac{R_n Bo}{1 + Bo} \tag{9}$$

$$\lambda E = \frac{R_n}{1 + Bo}. \tag{10}$$

The Bowen ratio can also be approximated through measurements of temperature and specific humidity alone. This equation only holds over inland continental regions

and on longer (daily to monthly) time scales, as it assumes land and atmosphere to be in equilibrium[1].

$$Bo \approx \frac{R_v c_p T_a^2}{\lambda^2 q_a} \tag{11}$$

T_a is the screen-level temperature (K), q_a is screen-level specific humidity (-), $cp = 1,005(Jkg^{-1}K^{-1})$ is the specific heat capacity of air at constant pressure, and $Rv = 461.5(Jkg^{-1}K^{-}1)$ is the gas constant for water vapor. The advantage of this equation is that there is no approximation of the temperature and humidity gradient, instead we can use surface temperature and humidity.

2 Instruments

2.1 Radiation

In this experiment short wave radiation components will be measured using a net-pyranometer that measures the upward and downward components separately. In addition net radiation (R_n) is measured using a net-radiometer. Both instruments are mounted on a portable tripod and can be deployed at different locations in the field.

2.2 Psychrometer

Air temperature and humidity will by measured using an aspiration psychrometer measuring temperatures at two ventilated thermometers. The first thermometer measures air temperature ("dry-bulb" temperature, T_a). The second thermometer is kept wet and measures the so called "wet-bulb" temperature (T_w). The difference between the dry-bulb and the "wet-bulb" temperature is directly related to the vapor pressure:

$$e = e_s(T_w) - \gamma \frac{p}{p_0}(T_a - T_w), \tag{12}$$

where $e_s(T_w)$ is the saturation vapor pressure at the wet-bulb temperature, γ is the psychrometric constant, p is the air pressure and $p_0 = 1000$ hPa. The saturation vapor pressure is specified as:

$$e_s(T) = 6.112 \times \exp\left(\frac{17.62 \times T}{243.12 + T}\right) \tag{13}$$

[1]McColl, K. A., & Rigden, A. J. (2020). Emergent simplicity of continental evapotranspiration. Geophysical Research Letters

3 Experiments

3.1 Think

Discuss the surface radiation balance and its components. Try to go beyond the equations listed in this document. Which factors determine the components? How would you, for instance, parametrize $LW_{\downarrow}$ and E?

3.2 Look

Have a look at the mobile instruments available at the field course and discuss how they (might) work.

3.3 Play

Play with the instrument, without breaking them of course. Measure under conditions that might not be scientifically meaningful, but reveil how the instruments work technically.

3.4 Measure

1. Choose a series of different environments for mobile radiation measurements.
2. At each location, determine:
   - the albedo (α)
   - the shortwave radiation balance ($SW_{\downarrow} - SW_{\uparrow}$)
   - the longwave radiation balance ($LW_{\downarrow} - LW_{\uparrow}$)
   - the latent (E) and sensible heat flux (H).
3. Estimate the accuracy of your measurements and calculations.

3.5 Discuss

1. What are the strong points of your observations and instruments?
2. What are the weak points of your observations and instruments?
3. Compare the values at the different locations and discuss differences.
4. Which research questions could be answered with the instruments at hand.