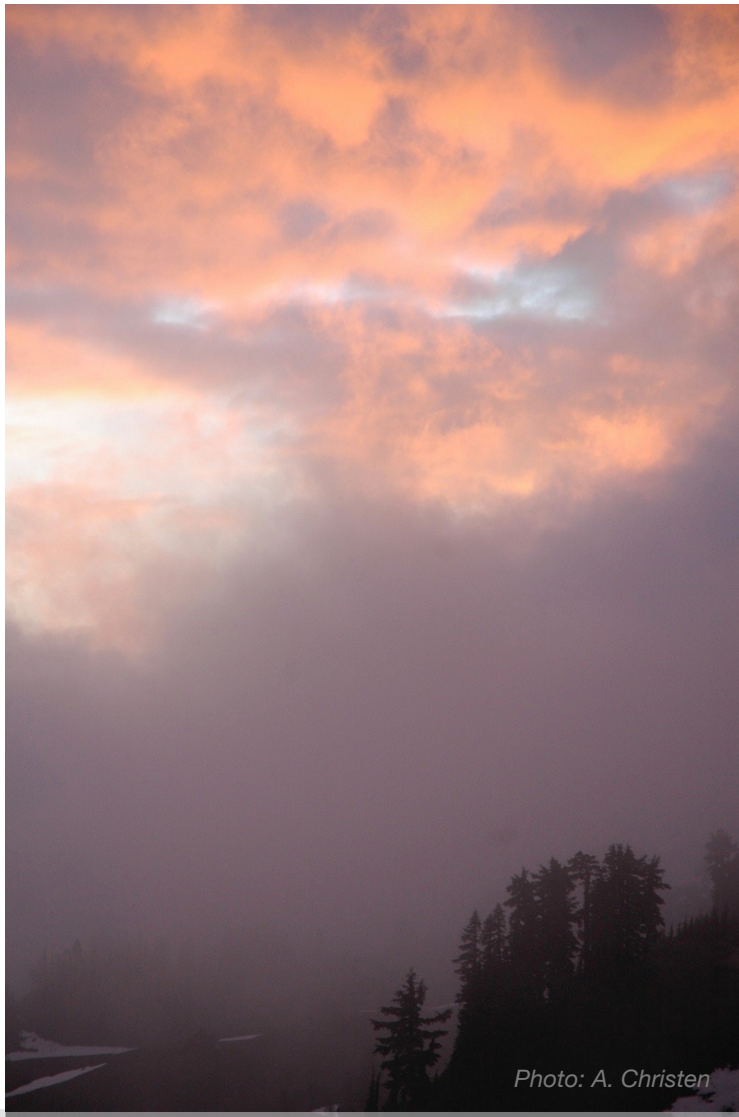
Measuring energy and water exchanges at a tidal marsh in Puget Sound (Photo: F. Anderson USGS)

03 Surface Energy Balance

Learning objectives

- Define the energy balance equation for an ideal surface.
- Describe how energy fluxes vary between daytime and nighttime.
- Define the Bowen ratio.
- Explain when can we reduce a 3D land-atmosphere interface to 1D.

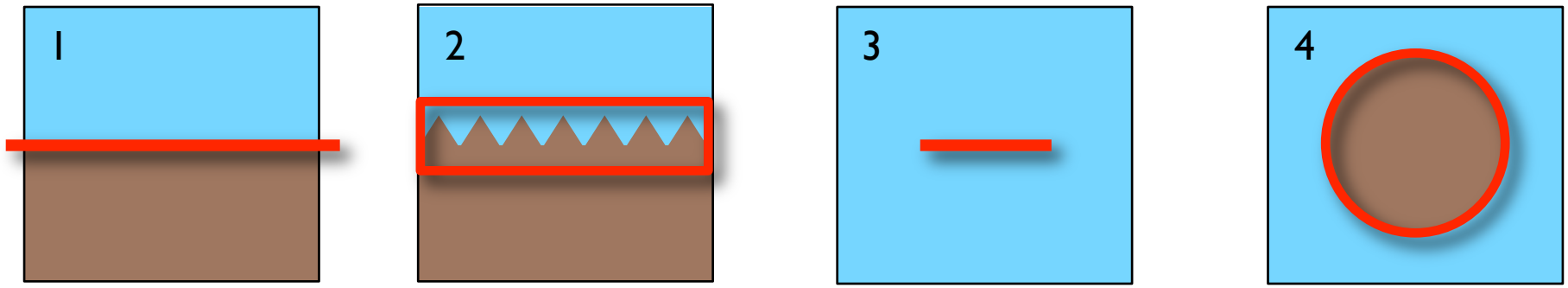


Why are we interested in the 'surface'?

- Ultimate goal: Predicting and managing surface-atmosphere interactions.
- Quantifying the impact of one system on another one.
- Understanding a system's interior dynamics (black box).

- Boundary condition:
  - Lower boundary condition for the ABL
  - Upper boundary for soil climates
  - Outer boundary for organisms and buildings

Types of surface-atmosphere interfaces



e.g.
bare soil
surface

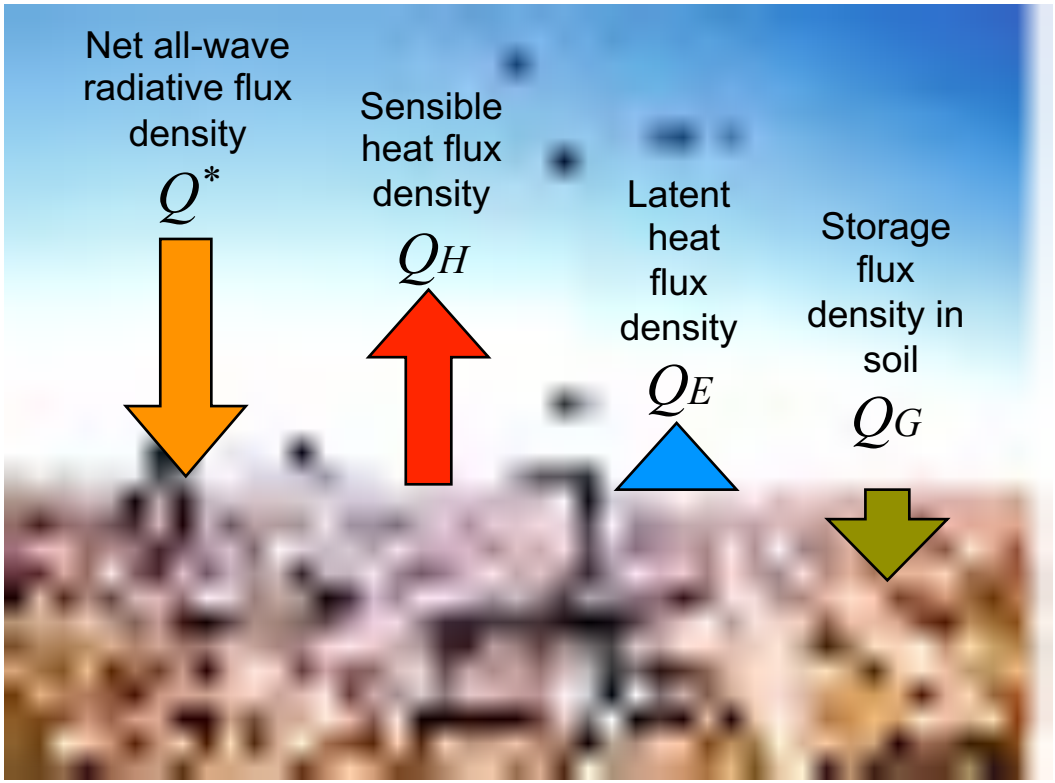
e.g.
forest
canopy

e.g.
leaf

e.g.
animal

Energy fluxes at Earth's surface – ideal surface

$$Q^* = Q_H + Q_E + Q_G \ \bigstar$$



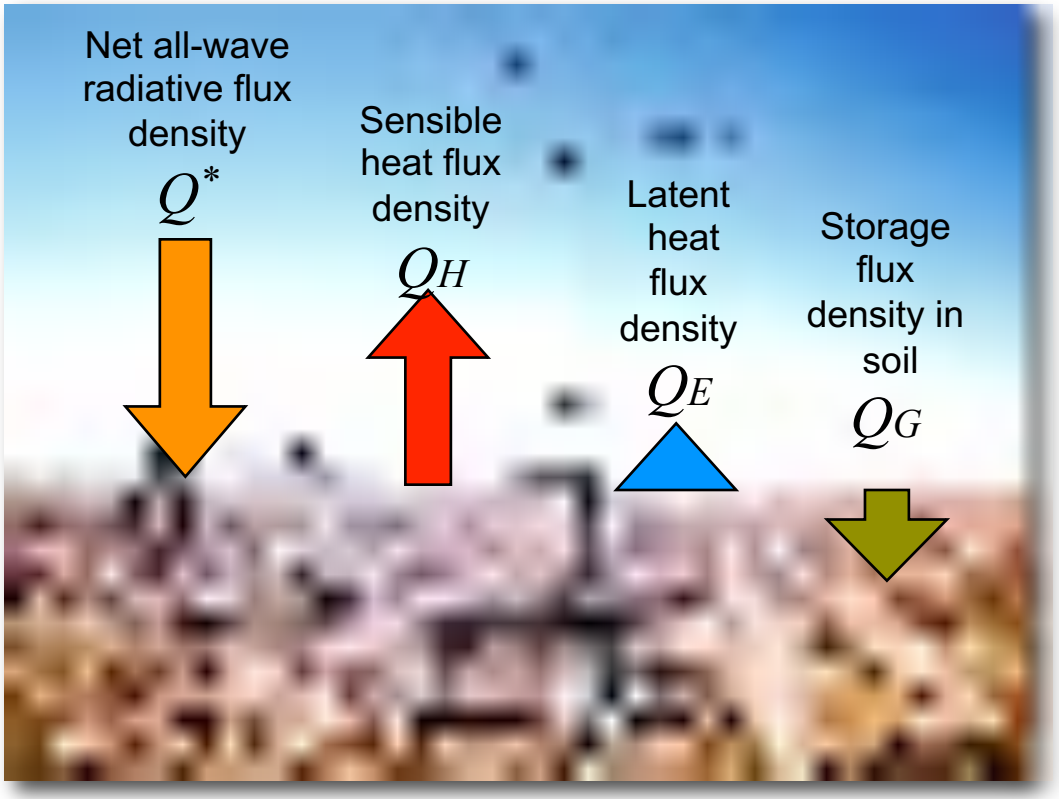
'Ideal' surface considered here is relatively smooth, horizontal, homogeneous, extensive, and opaque to radiation.

Only vertical fluxes need to be considered.

Sign convention

- All the radiative fluxes directed toward the surface are positive.
- Other (nonradiative) energy fluxes directed away from the surface are positive.

$$Q^* = Q_H + Q_E + Q_G$$ ★

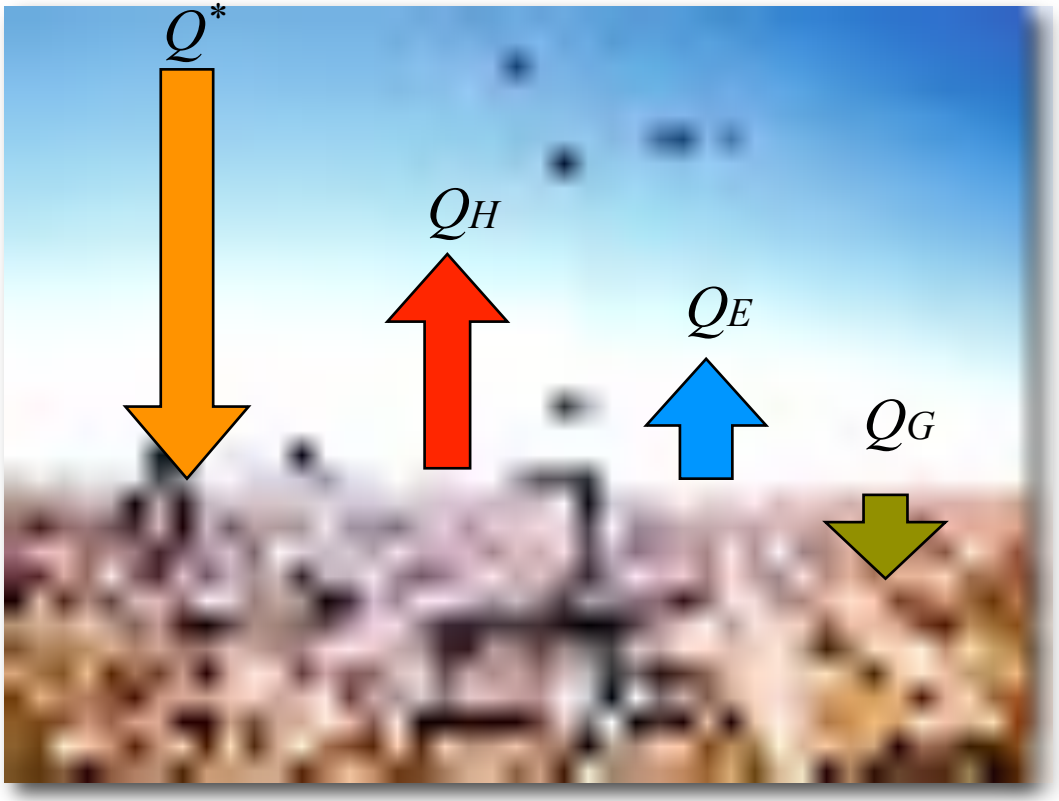


Daytime

Typically:

- $Q^* > 0$
- Q_H, Q_E, and Q_G are all positive over land surfaces during the day

$$Q^* = Q_H + Q_E + Q_G$$ ★



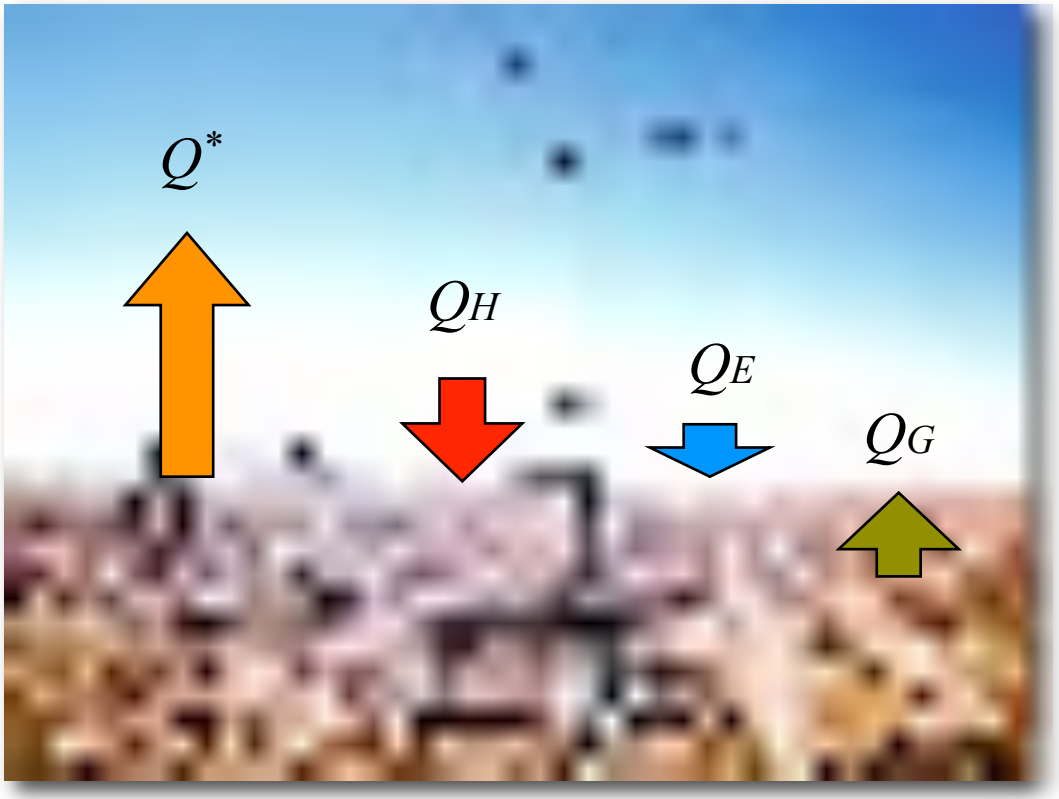
Nighttime

Typically:

- Fluxes are negative

- Fluxes are smaller in magnitude

$$Q^* = Q_H + Q_E + Q_G$$ ★

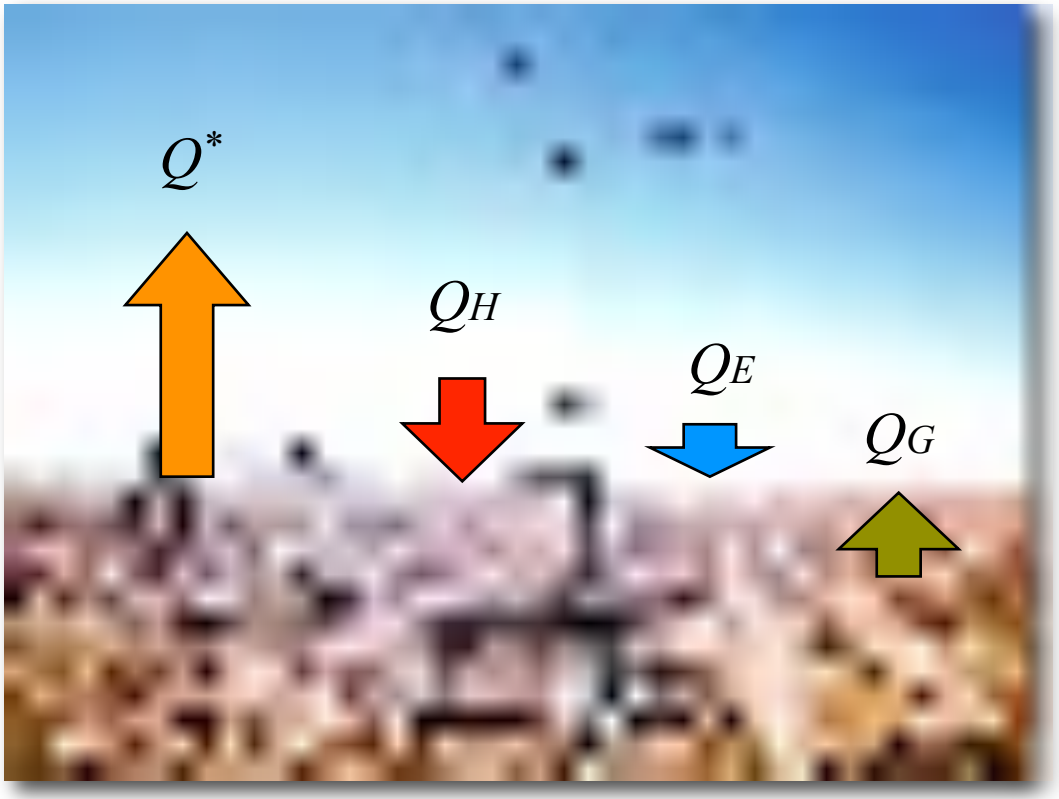


Bowen ratio (B)

$$Q^* = Q_H + Q_E + Q_G$$

The Bowen Ratio (*B*) is used to express the partitioning of net radiation at a surface.

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



Test your knowledge

Question 1 – fill in the table

Energy balance equation: $Q^* = Q_H + Q_E + Q_G$

Symbol & Units	Name	Daytime (sign)	Nighttime (sign)
Q^*			
Q_H			
Q_E			
Q_G			

Test your knowledge

Illustrate the typical surface energy balance for:

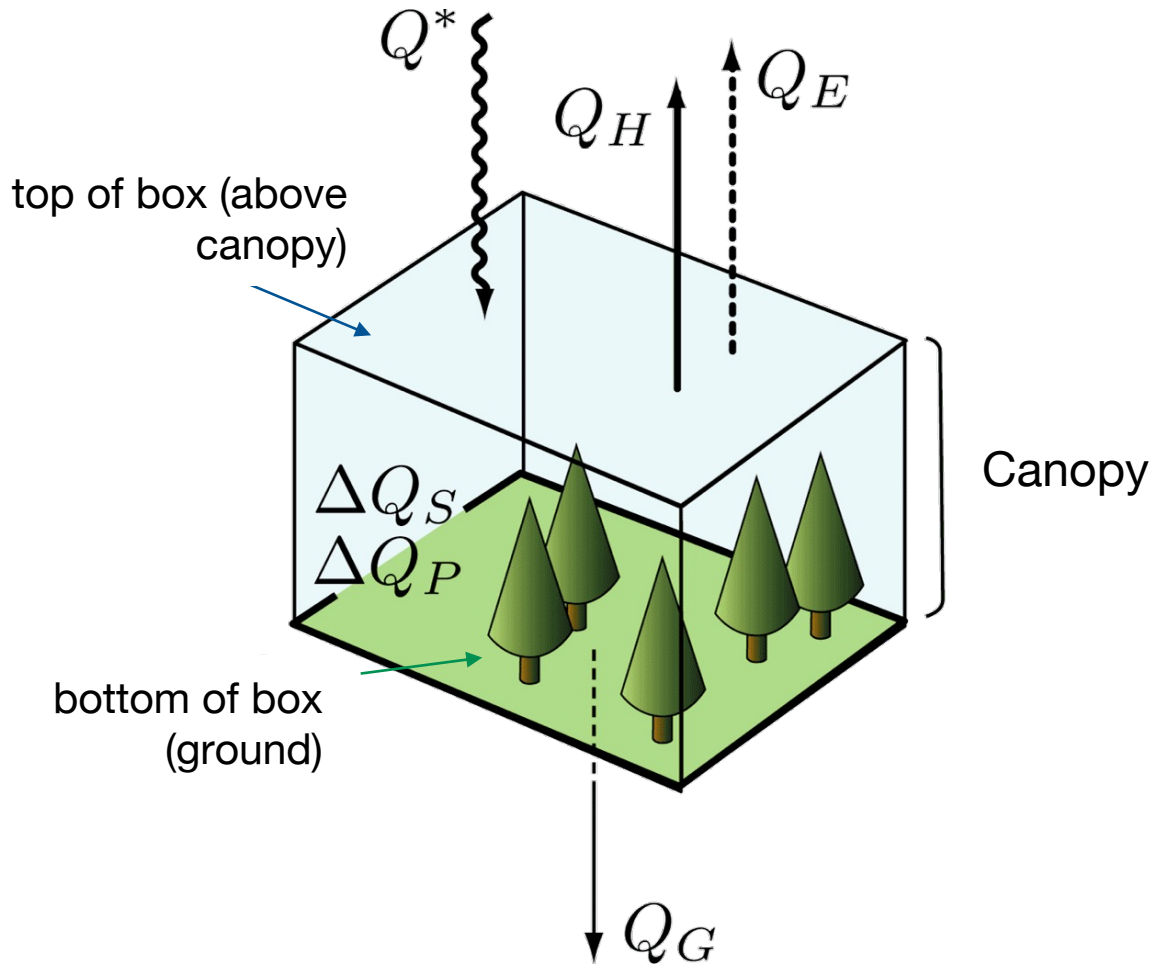
Daytime

Nighttime

Photo: A. Christen

Photo: A. Christen

The volume view – 3D land-atmosphere interfaces



Review - Assuming horizontal homogeneity.

For a number of variables in the ABL we find that on average:

overbar means average over a longer time (e.g. an hour to avoid turbulent variations)

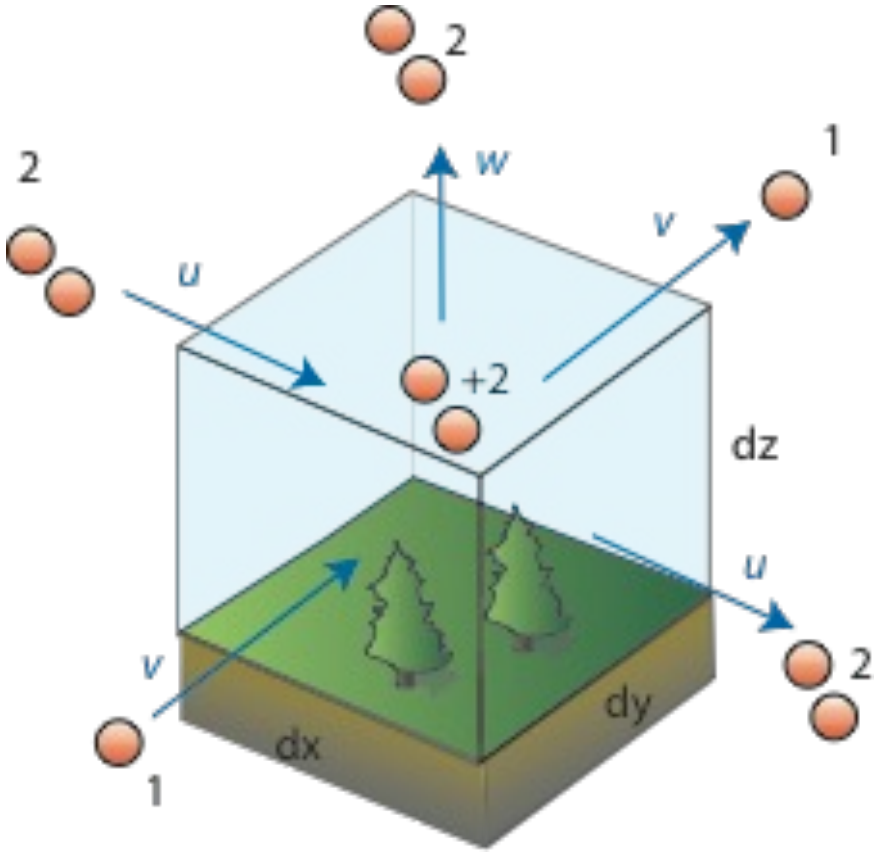
$$\frac{\partial \overline{o}}{\partial x} \text{ and } \frac{\partial \overline{o}}{\partial y} \ll \frac{\partial \overline{o}}{\partial z}$$

(e.g. for u, v, p, T, q, c)

Over flat and homogeneous terrain we simplify situations in micrometeorology / climatology to a horizontally homogeneous case i.e. where the mean horizontal gradients vanish:

$$\frac{\partial \overline{o}}{\partial x} = \frac{\partial \overline{o}}{\partial y} = 0$$

Reducing a 3D land-atmosphere interface to 1D



Then, we can assume that the advection by mean wind on opposite sides of the 'box' cancel each other out, i.e.

$$u\frac{\partial \overline{\bigcirc}}{\partial x} = v\frac{\partial \overline{\bigcirc}}{\partial y} = 0$$

This does means that only vertical exchange at top of the box is considered. Indeed many parameteriations are **one-dimensional**

Base image from J. J. Finnigan (2004)

Energy balance of a 3-dimensional interface.

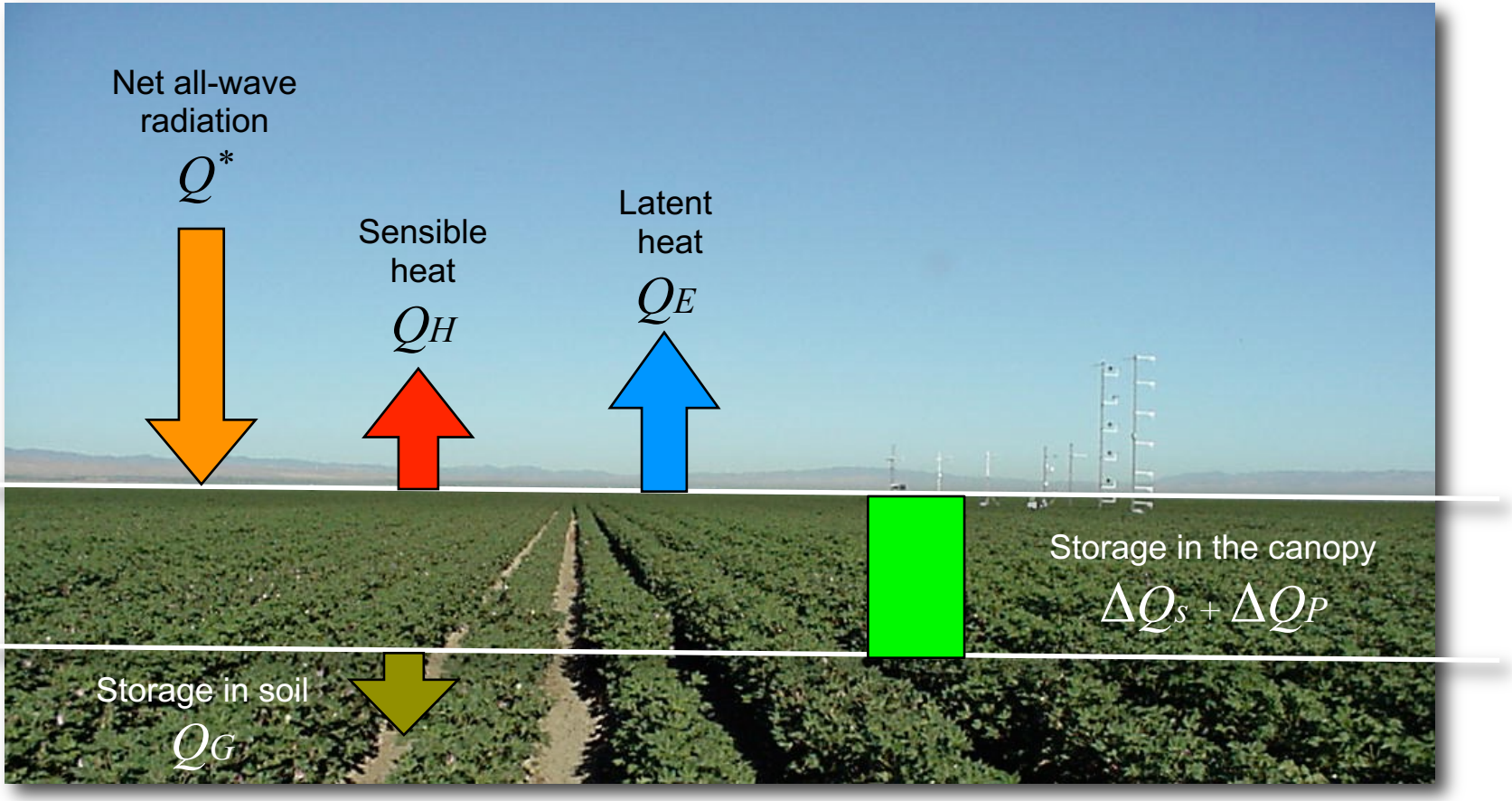


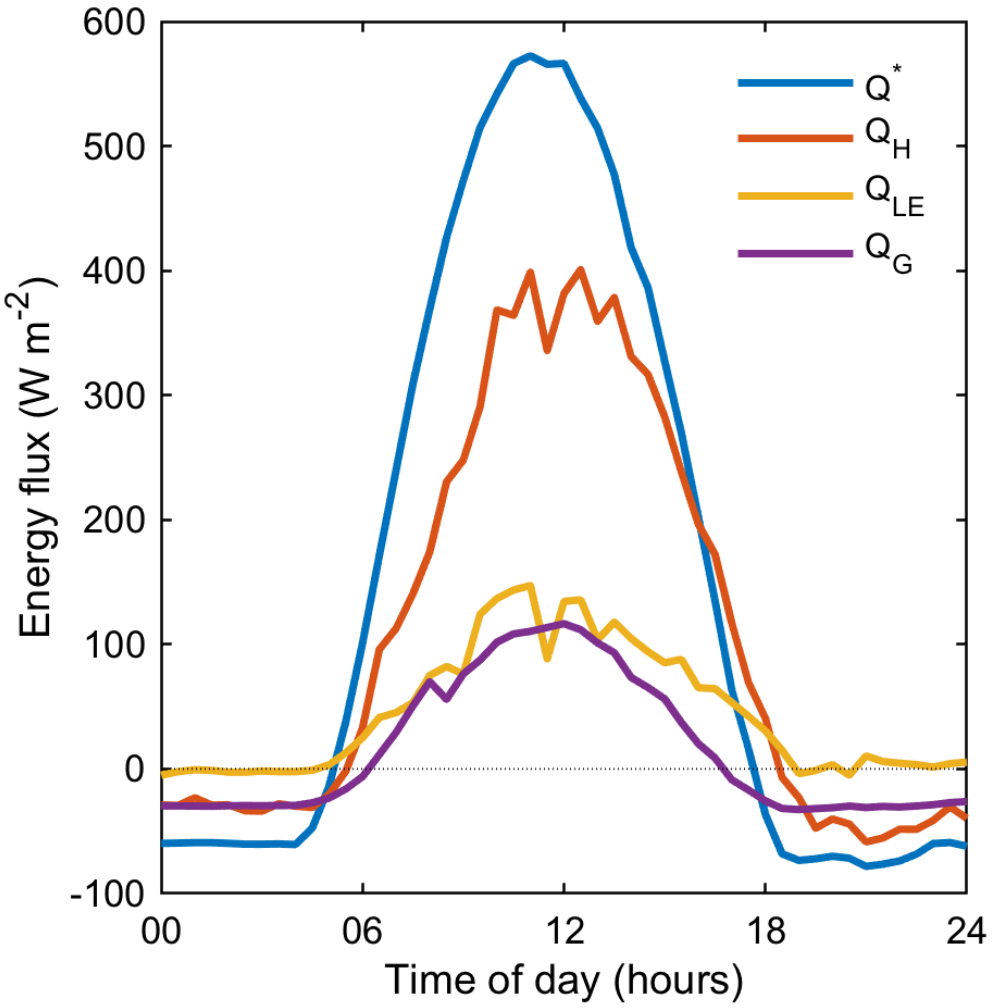
Photo: A. Christen

Storage within the interface.

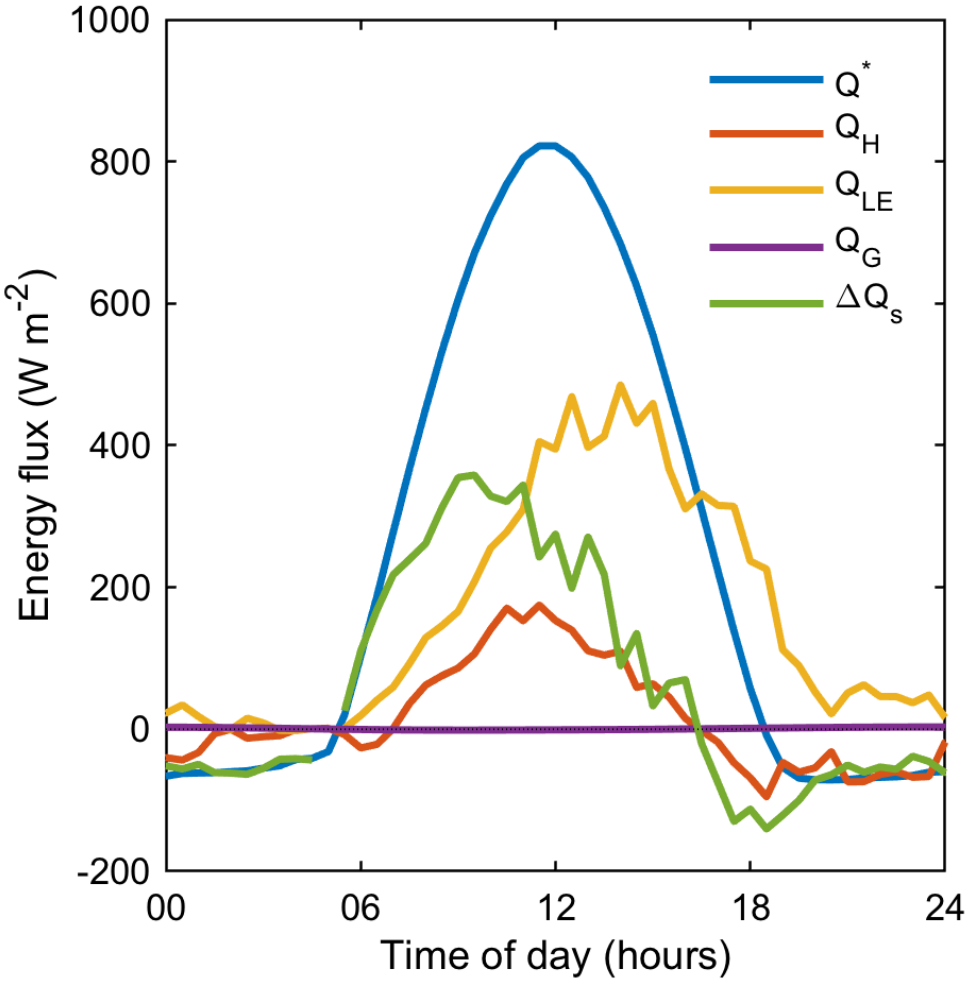
- ΔQ_P Net biochemical energy storage in the biomass through photosynthesis minus respiration.
- $\Delta Q_{S,B}$ Net sensible heat storage in the biomass.
- $\Delta Q_{S,H}$ Net sensible heat storage in the canopy air volume.
- $\Delta Q_{S,E}$ Net latent heat storage in the canopy air volume.

Measurement of the sensible heat storage in the biomass using thermocouples measuring the rate of temperature change of different plant parts during EBEX-2000.

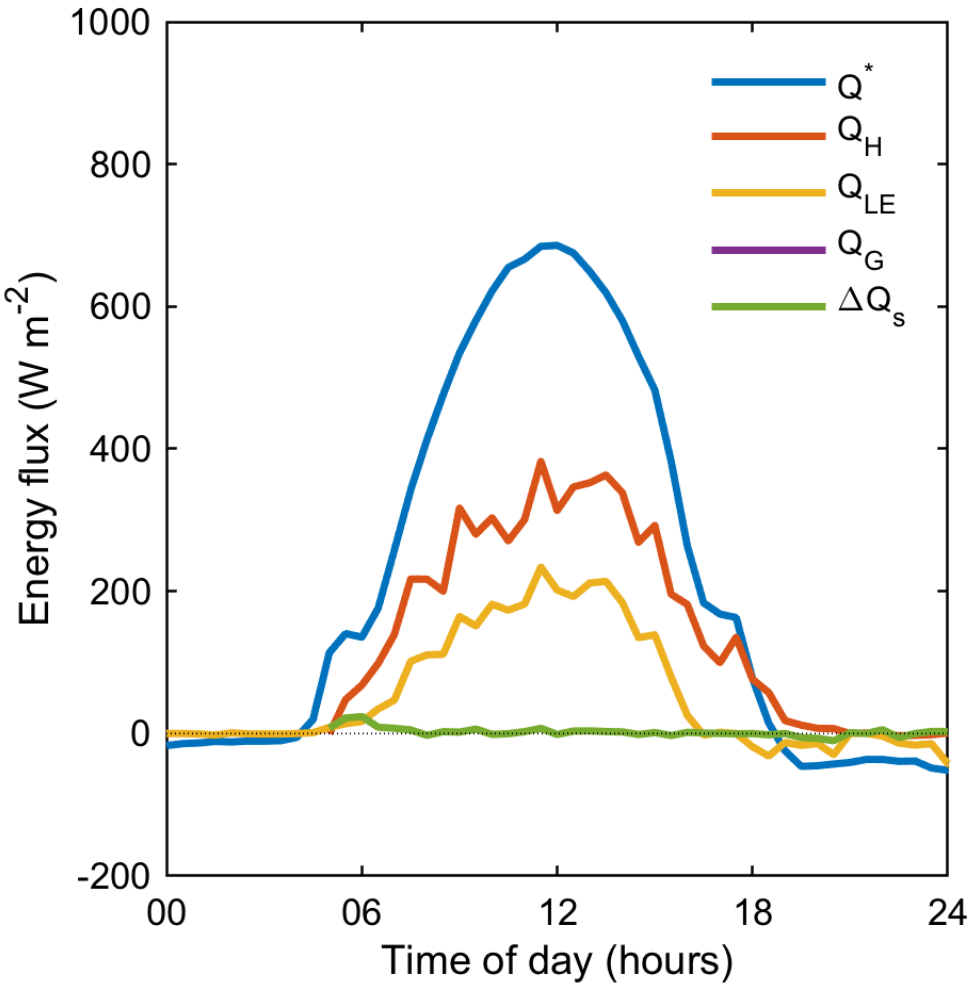
Real world examples: Fallow rice field



Real world examples: Freshwater marsh

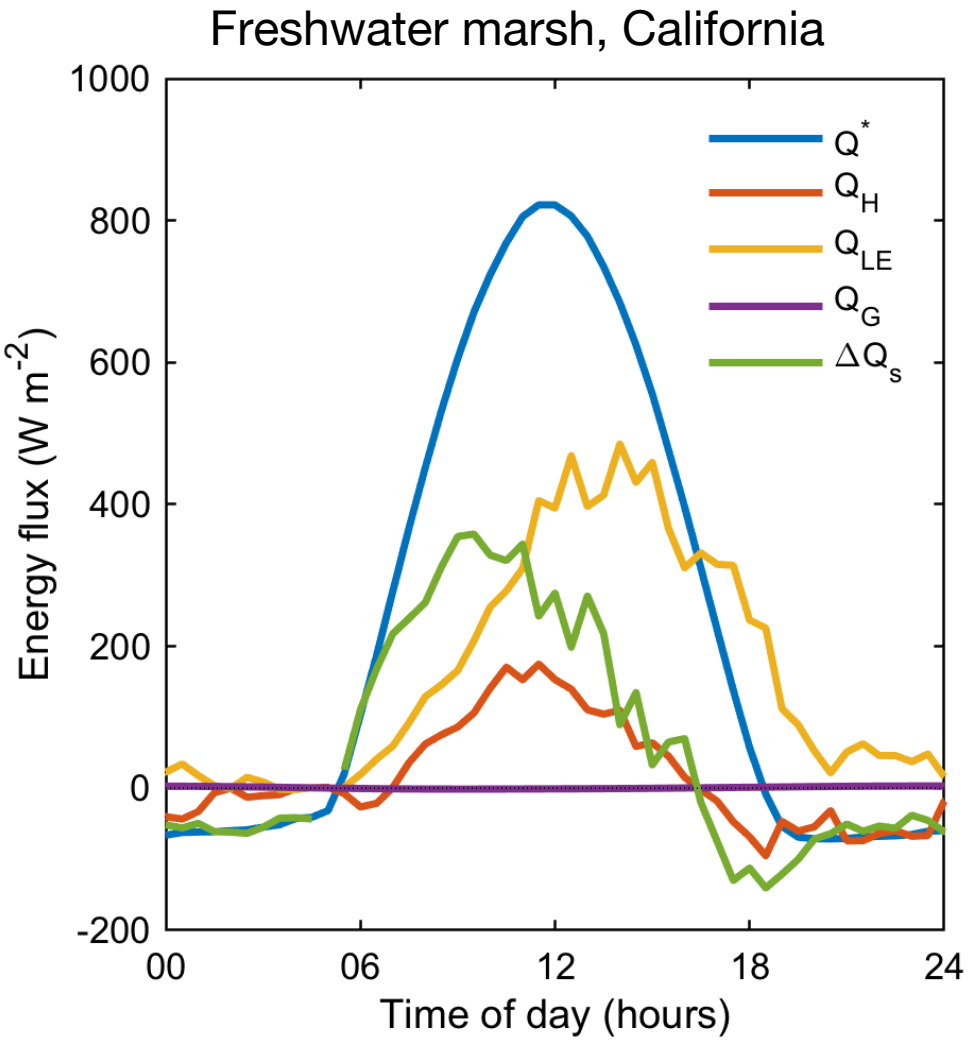


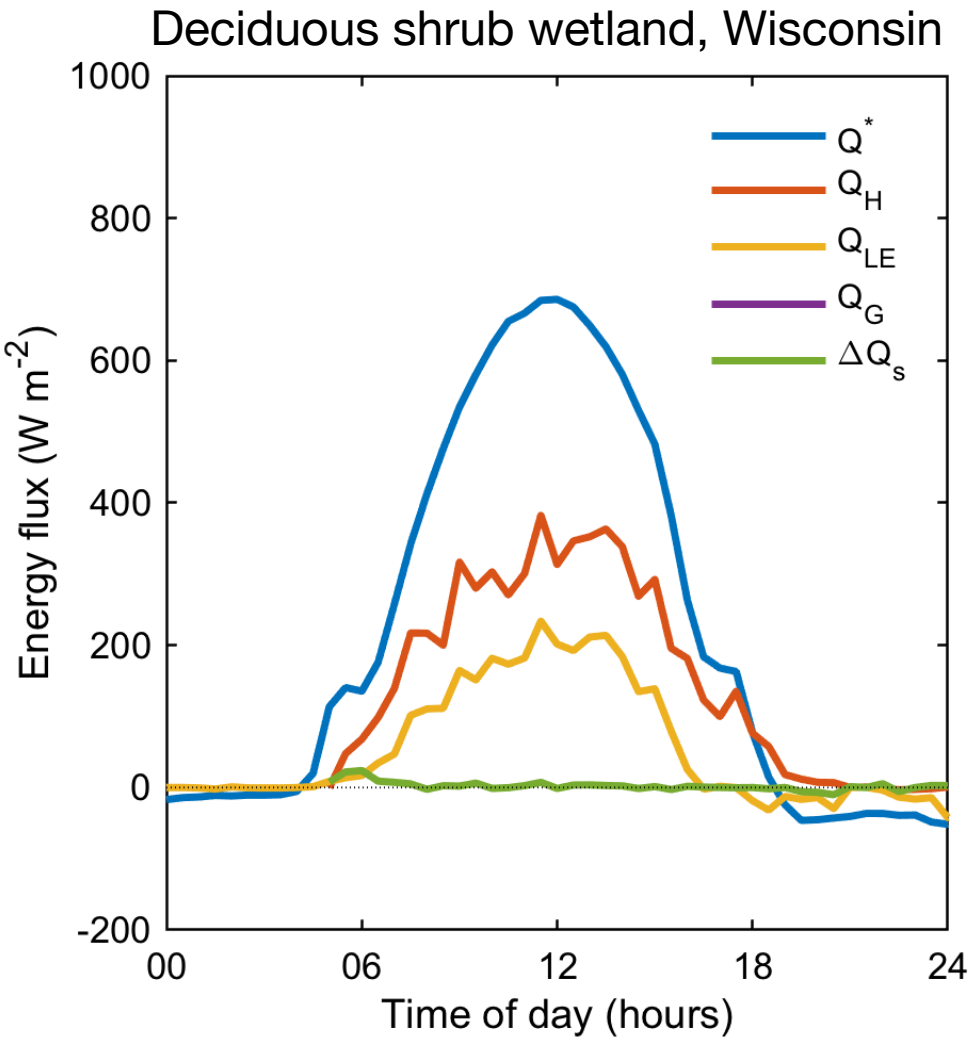
Real world examples: Deciduous shrub wetland



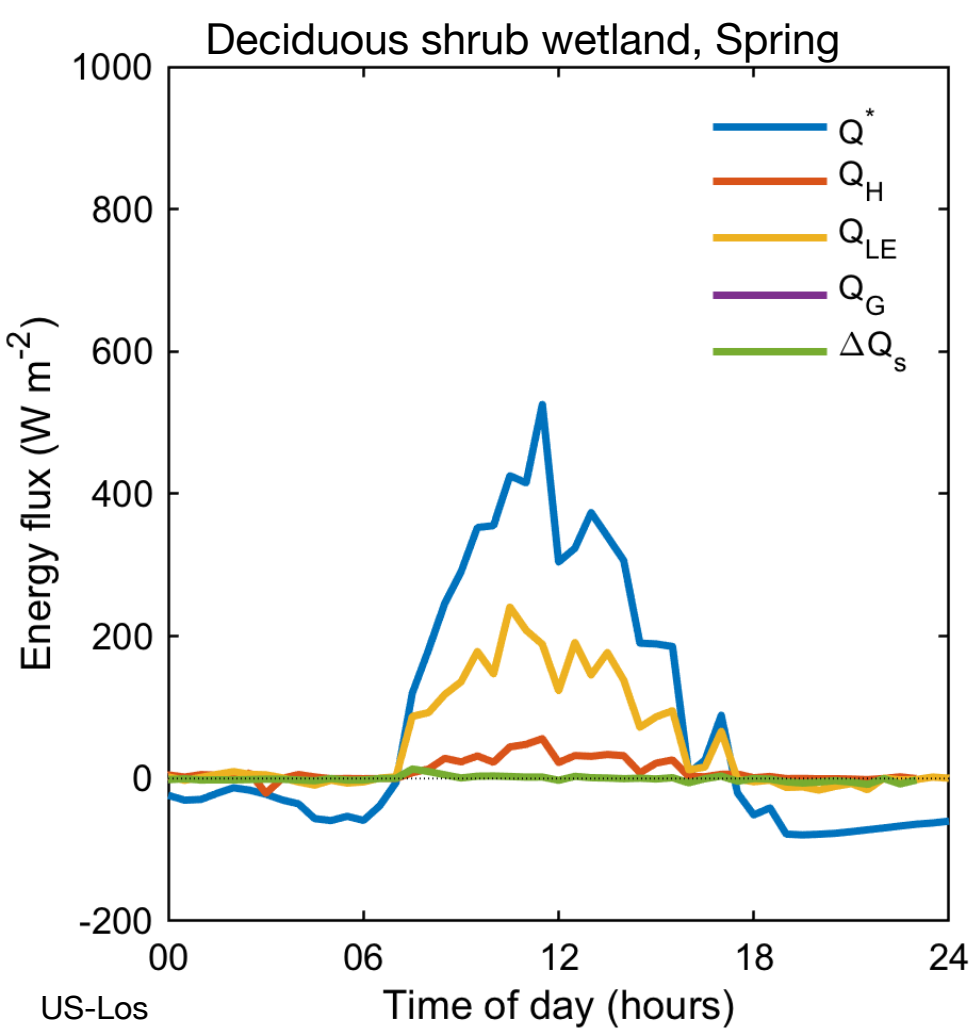
Test your knowledge – Which site has a larger Bowen ratio? (Slido)

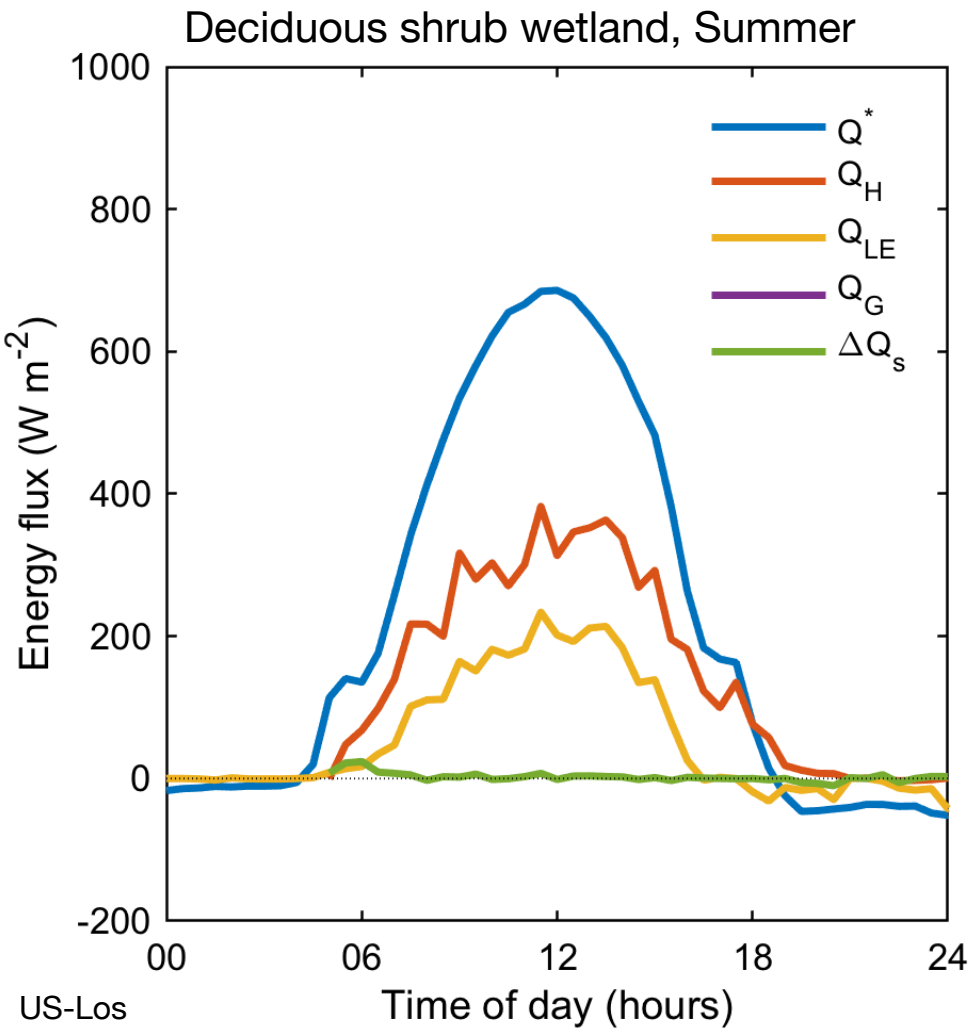
Actual magnitudes highly variable (e.g. location, surface type, time of day)





Actual magnitudes highly variable (e.g. season, weather)





Energy balance of a two-sided object.

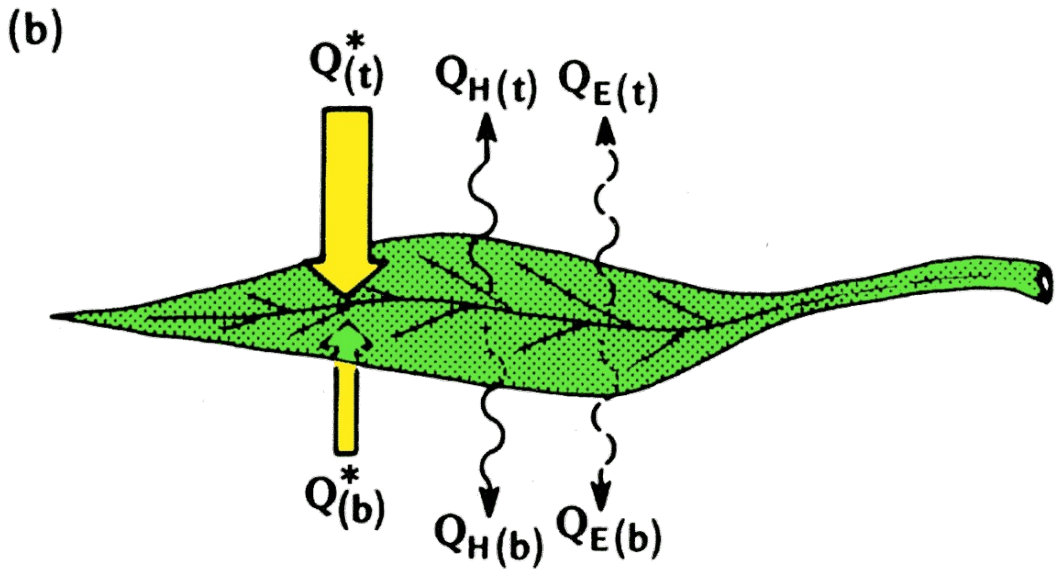


Figure 4.5 Schematic depiction of the fluxes involved in (a) the radiation budget and (b) the energy balance of an isolated leaf.

T.R. Oke (1987): 'Boundary Layer Climates' 2nd Edition.

A surface within a single medium (e.g. a leaf surrounded by air).

No third dimension, so heat storage is neglected.

Energy flux densities on both sides have to be taken into account.

Orientation of the surface is important for exchange processes (radiation).

Applications

- The energy budget over terrestrial surfaces is a key determinant of the land surface climate and governs a variety of physical, chemical and biological surface processes.
- Estimation of the rate of evaporation from bare ground and water surfaces and evapotranspiration from vegetative surfaces.
- Prediction of surface temperature.

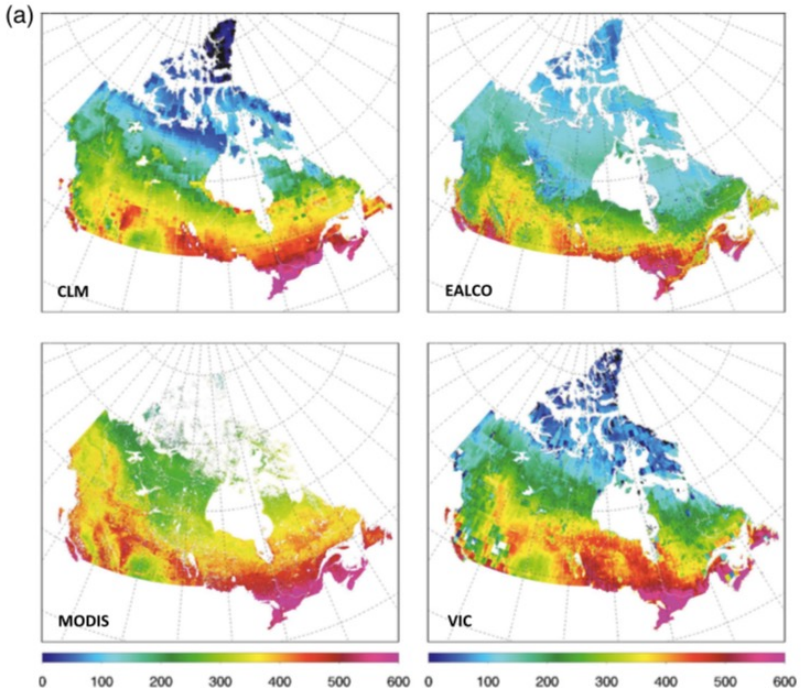


FIG. 3. (a) Mean annual ET (mm yr^{-1}) from CLM, EALCO, MOD16, and VIC. Negative values are in black. MOD16 has 25.5% of the area with no data, primarily in the Arctic. (b) Histogram of mean annual ET (10 mm yr^{-1} bins) from CLM, EALCO, MOD16, and VIC. Note that MOD16 dataset has large gaps over the north, as shown in (a).

Wang et al. 2015

Take home points

- Land-atmosphere interfaces are complex boundaries, with significant energy and mass exchange.
- We covered the **surface energy balance** of (1) flat surfaces, (2) canopies, and (3) two-sided objects.
- The **Bowen ratio** of the ratio of sensible to latent heat.
- We explored how the surface energy budget **varies** by surface type and its characteristics (soil moisture, texture, vegetation, etc.), geographical location, month or season, time of day, and weather.