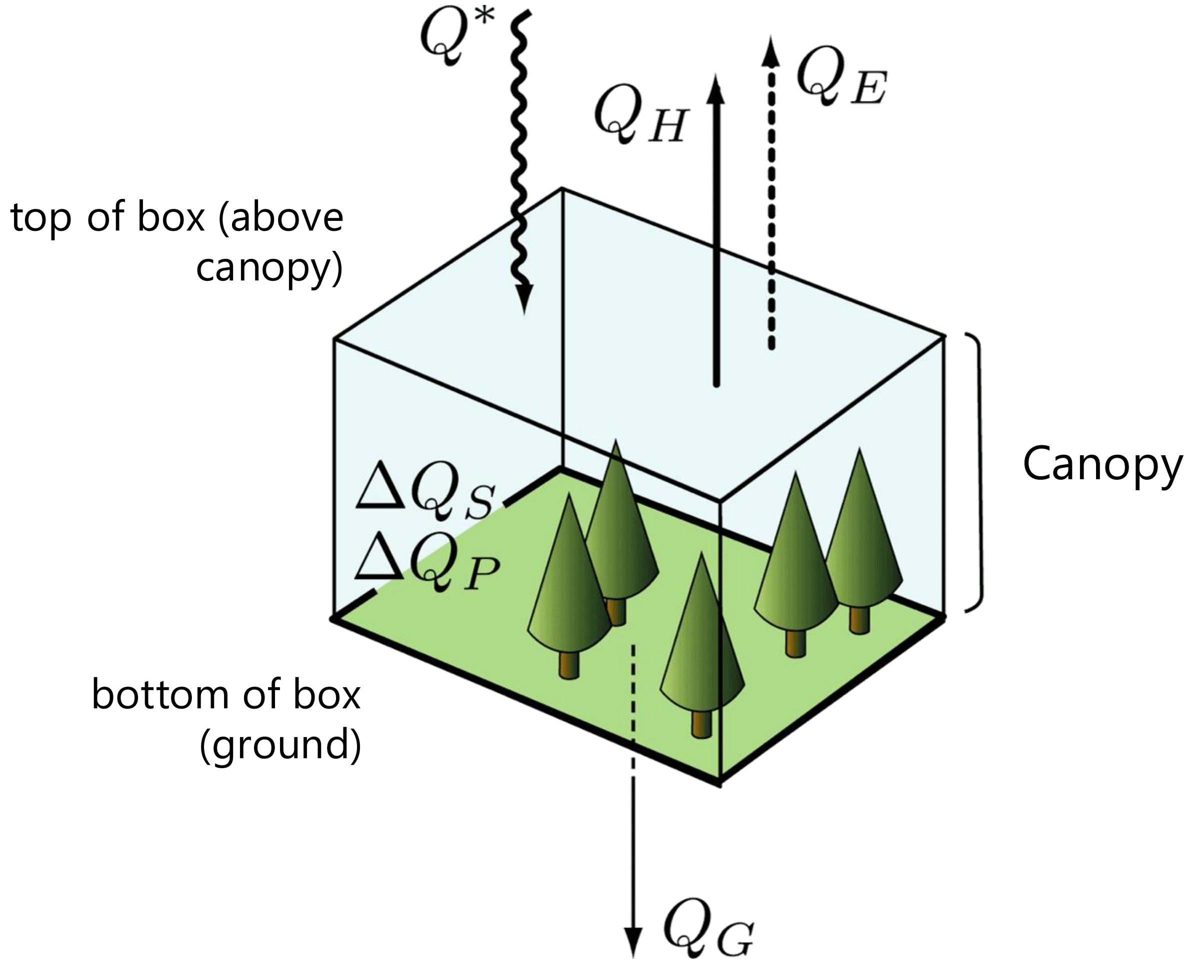
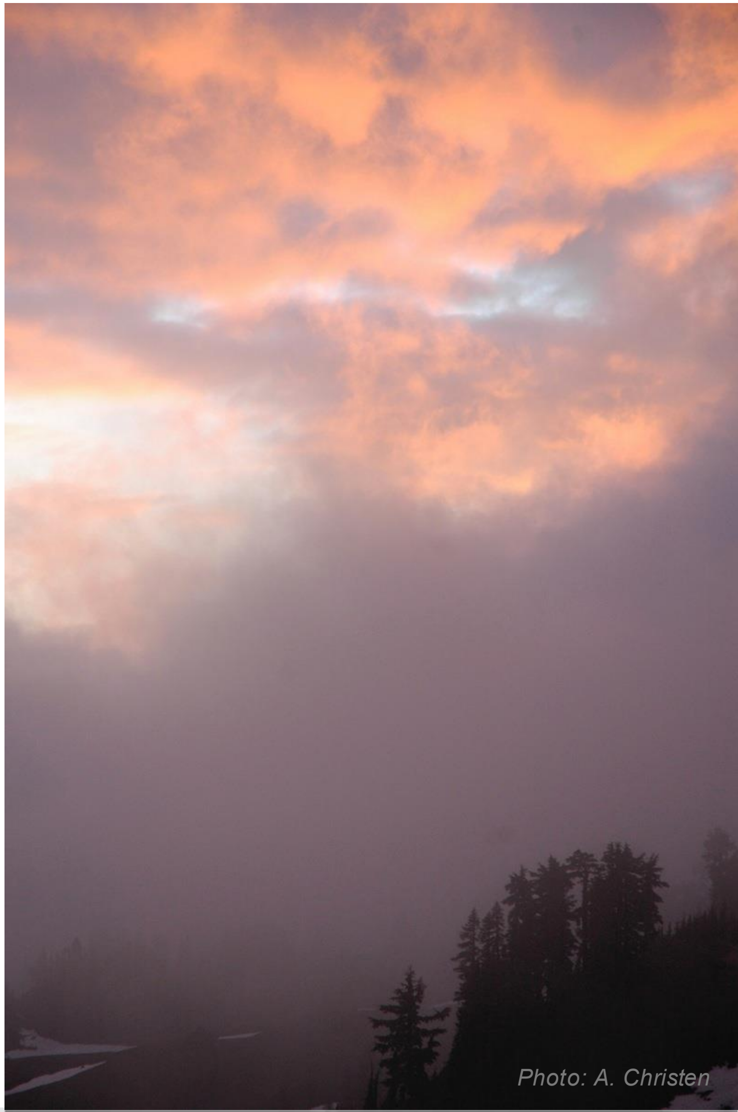


02 & 03 Energy & mass balances, and surface energy balance

Learning objectives

- Describe how we can we track energy and mass in the atmosphere.
- Describe and simplify exchange processes of energy and mass at surface-atmosphere interfaces (from 3D to 1D).
- Define the energy balance equation for an ideal surface.
- Describe how energy fluxes vary between daytime and nighttime.
- Define the Bowen ratio.
- Review: Define the dominant energy and mass transfer mechanisms in the atmosphere.



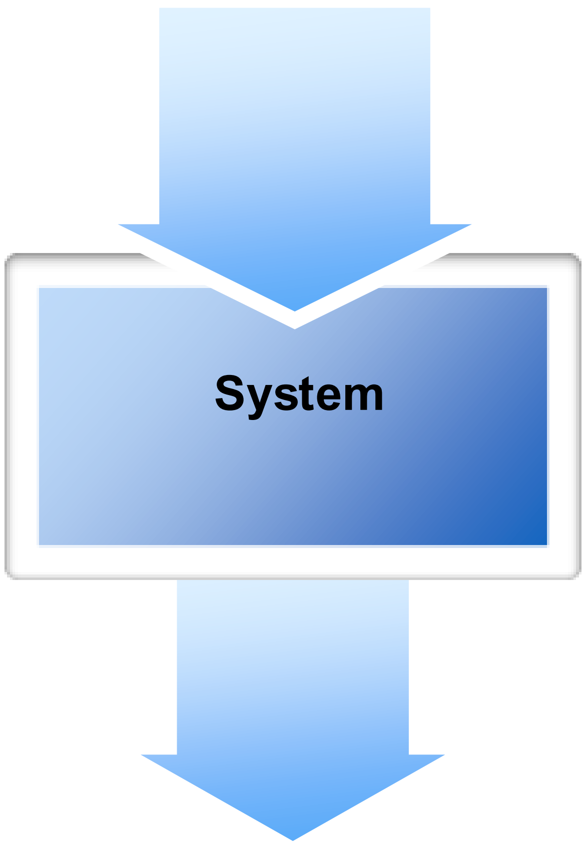
Conservation of energy and mass

One of the most powerful laws used in micrometeorology is this **law of conservation**.

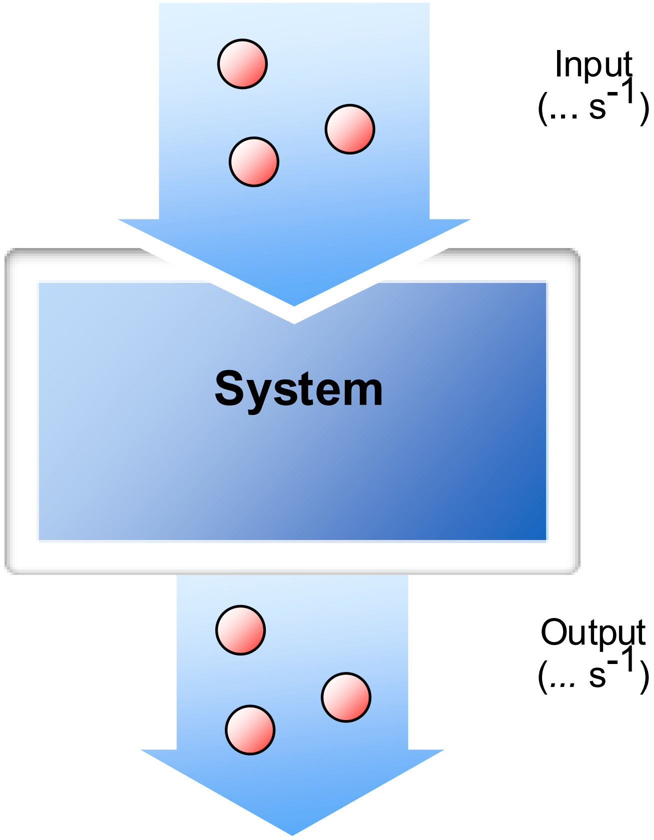
Neither mass nor energy can be created or destroyed by any ordinary means. We can convert energy from one form to another and move it around.

Energy of importance to climatology exists in the Earth-Atmosphere system in four different forms (radiant, thermal, kinetic and potential) and is continually being transformed from one to another.

Conservation of energy and mass

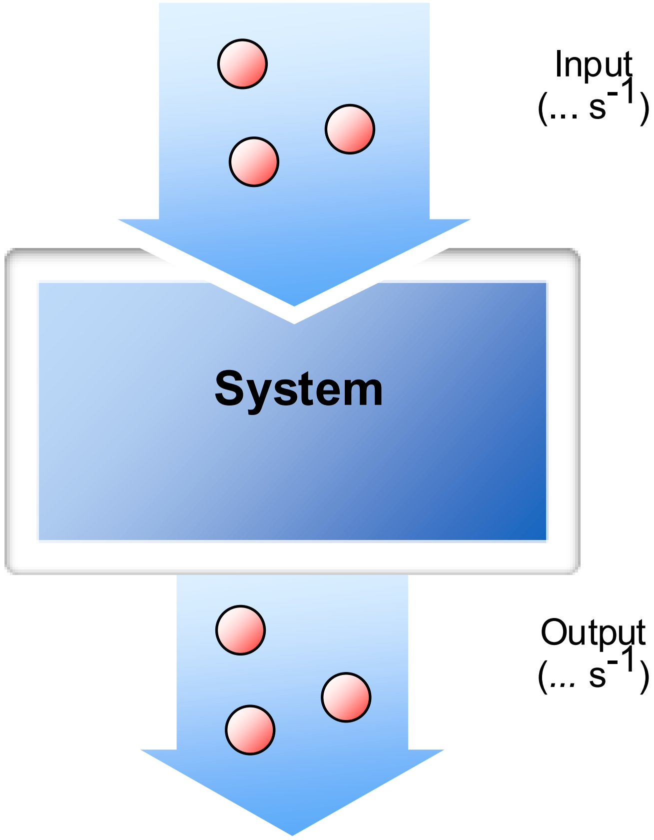


Input = Output

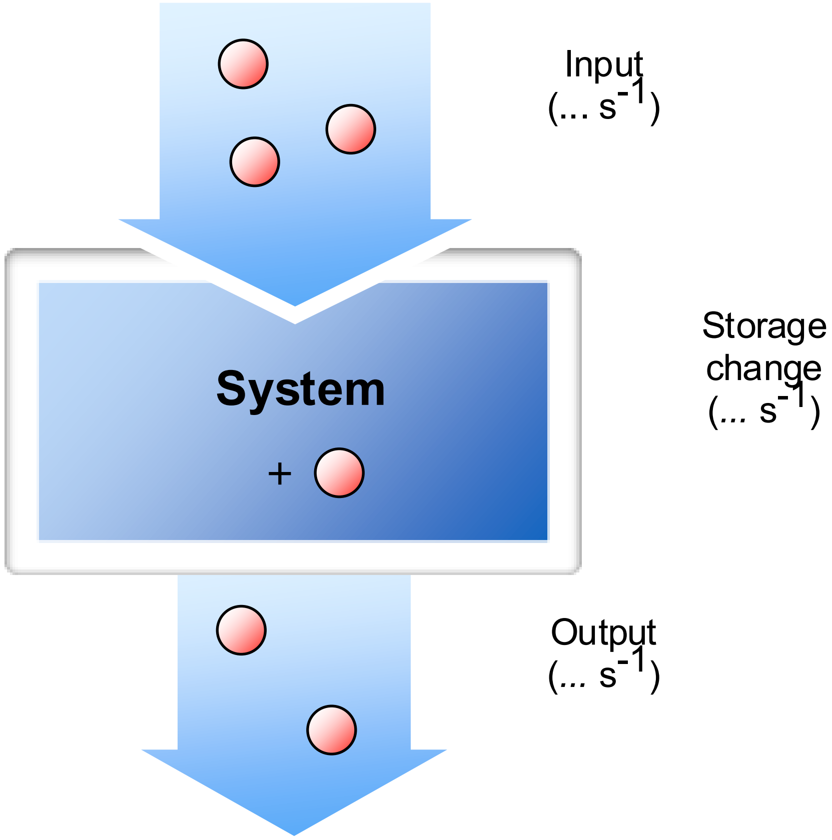


Input - Output = 0

Input – Output = Storage change

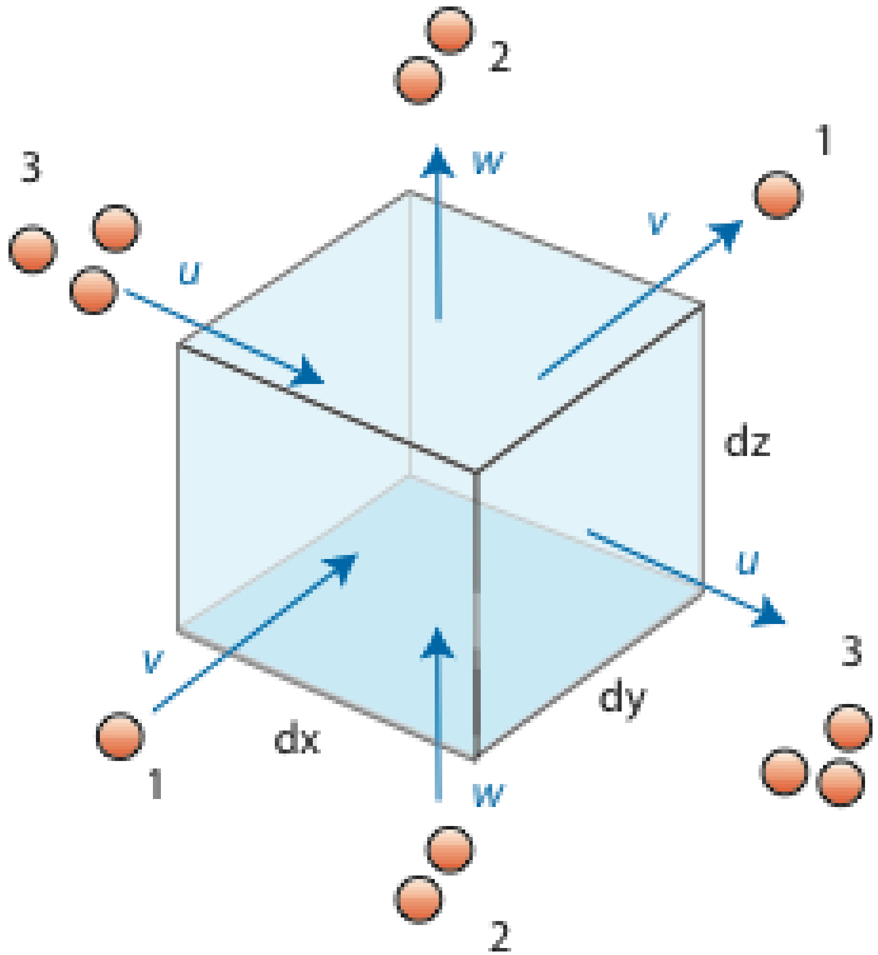


Input - Output = 0



Input - Output = Storage change

Conservation in a three-dimensional box



input		output		storage
$(3u+1v+2w)$	-	$(3u+1v+2w)$	=	0

divergence free case

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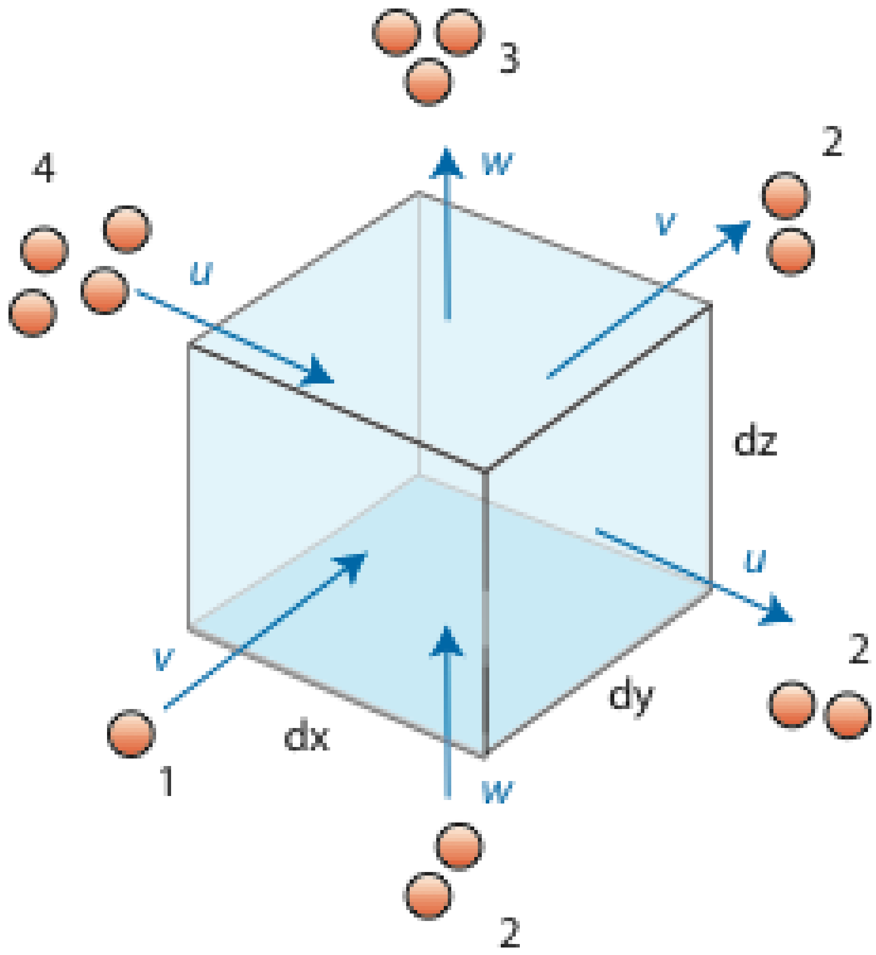
What is the change in storage?



input output storage

What is the change in storage in this case?

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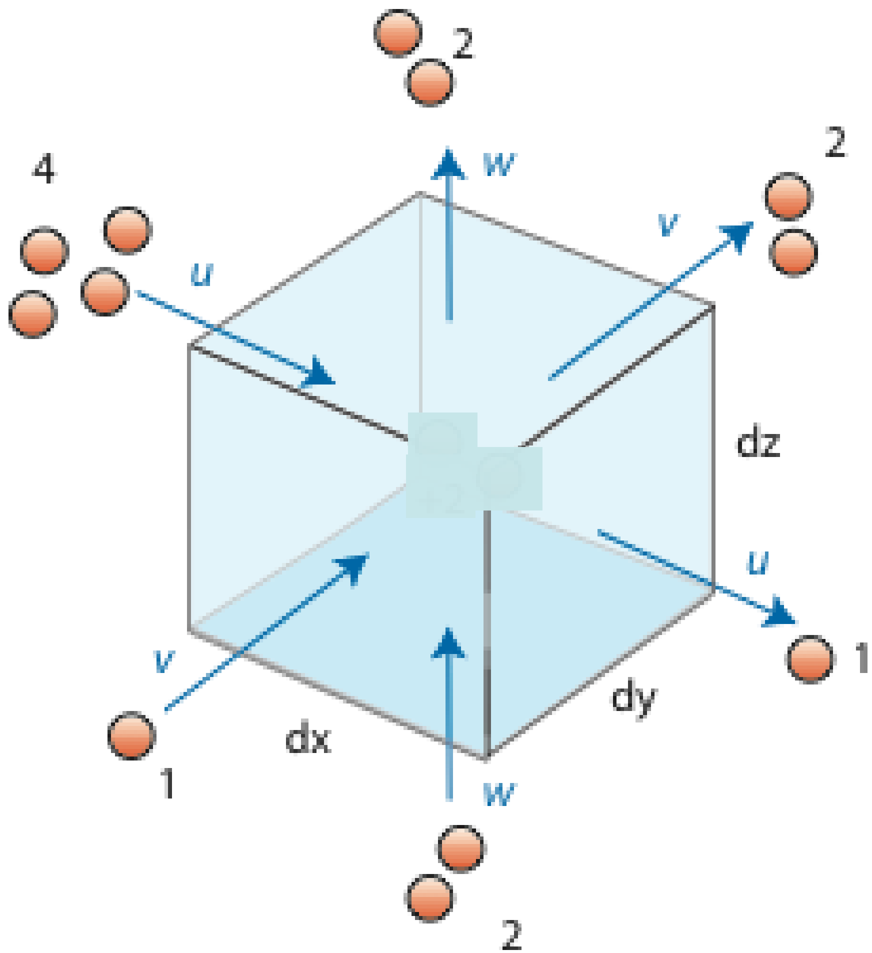
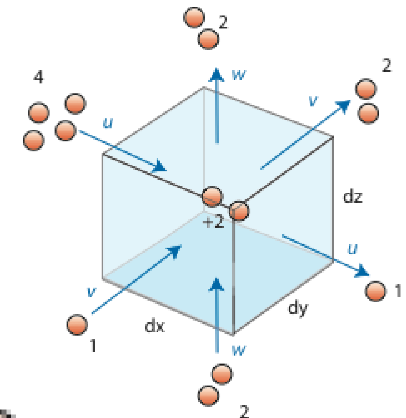


input

output

storage

Conservation of a scalar in three dimensions



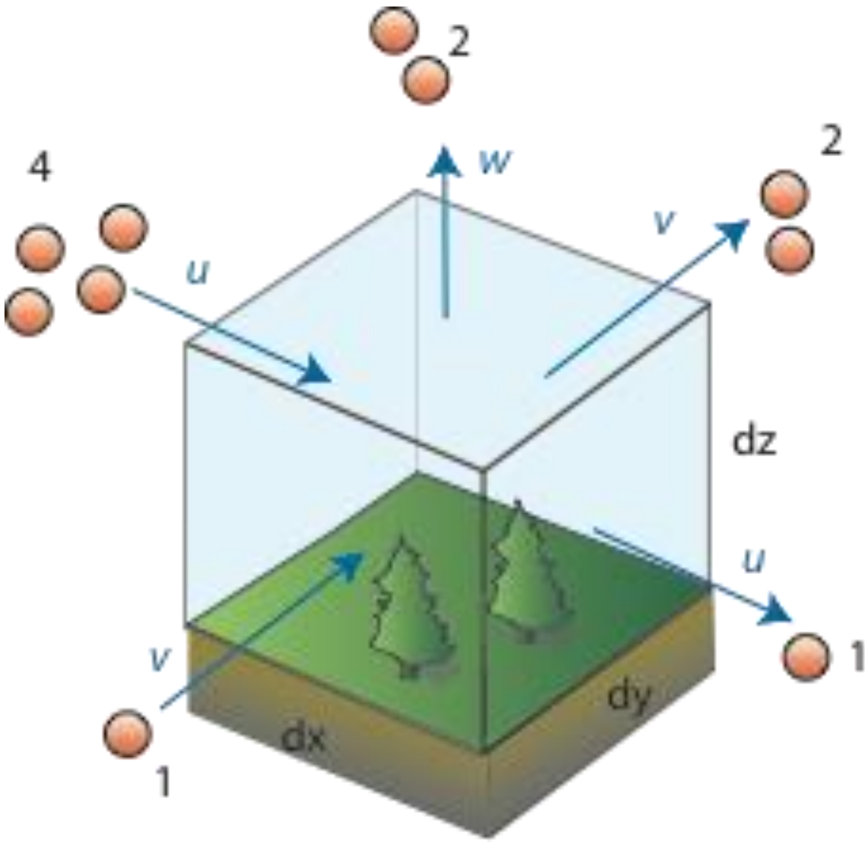
total derivative
(change in entire system)

partial derivatives
(changes in time or space)

$$\frac{d\bullet}{dt} = \frac{\partial\bullet}{\partial t} + \underbrace{u\frac{\partial\bullet}{\partial x} + v\frac{\partial\bullet}{\partial y} + w\frac{\partial\bullet}{\partial z}}$$

total change — storage change — Advection (input / output by wind)

Conservation at a land-interface



no wind is able to enter box from below, hence no transport from below by wind (diffusion is still an option)

input		output	storage
($4u$+$1v$)	-	($1u$+$2v$+$2w$)	= 0

Assuming horizontal homogeneity.

For a number of variables in the ABL we find that <u>on average</u>:

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

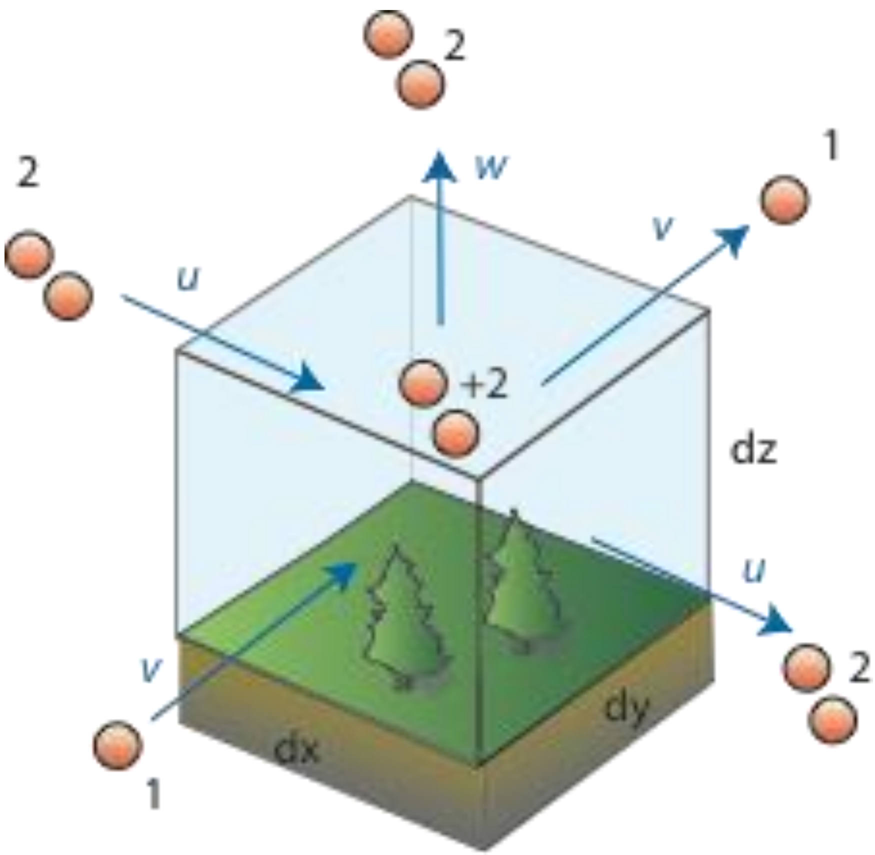
$$\frac{\partial \overline{\bigcirc}}{\partial x} \text{ and } \frac{\partial \overline{\bigcirc}}{\partial y} \ll \frac{\partial \overline{\bigcirc}}{\partial z}$$

(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:

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

Reducing a 3D land-atmosphere interface to 1D

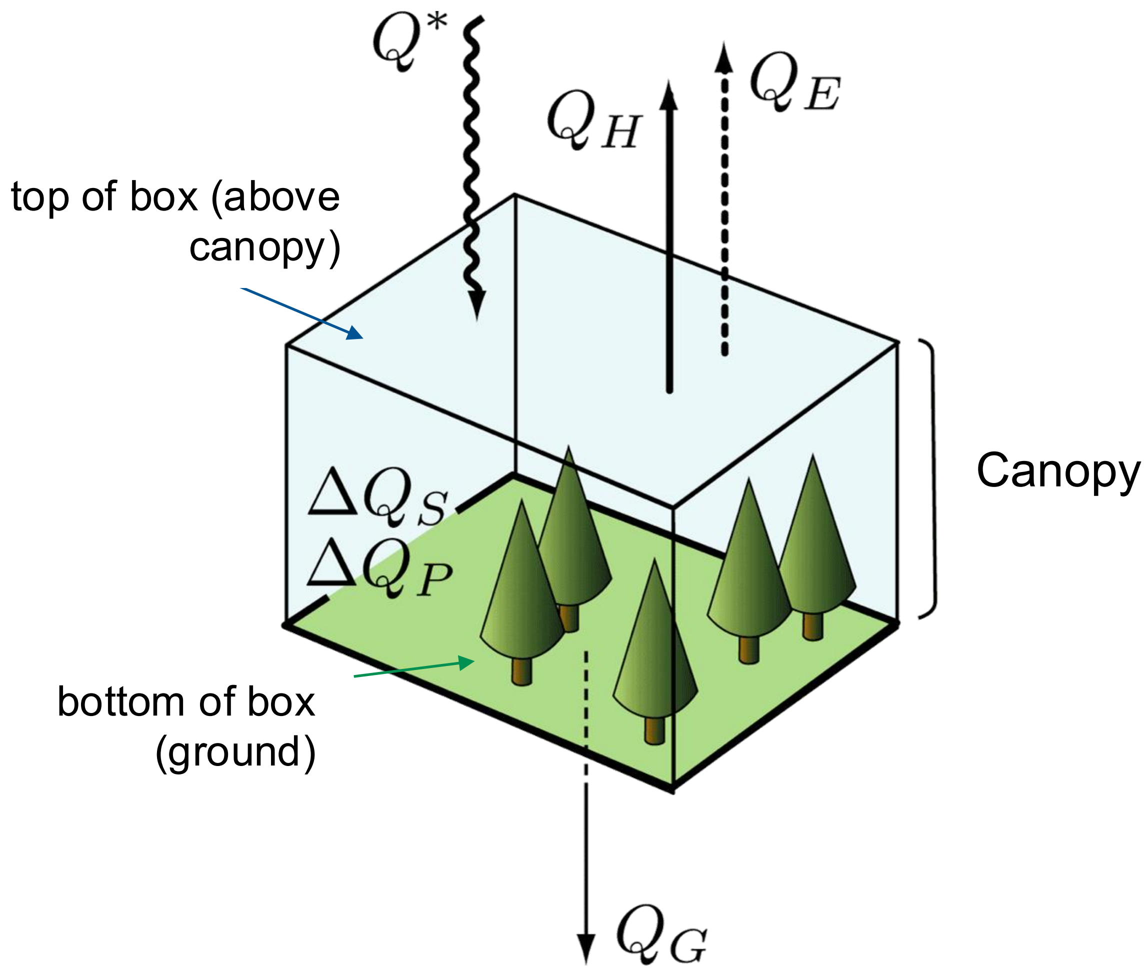


Then, we can assume that the advection by mean wind on opposite sides of the 'box' cancel each other out, i.e.

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

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

Real world examples – simplifying 3D to 1D

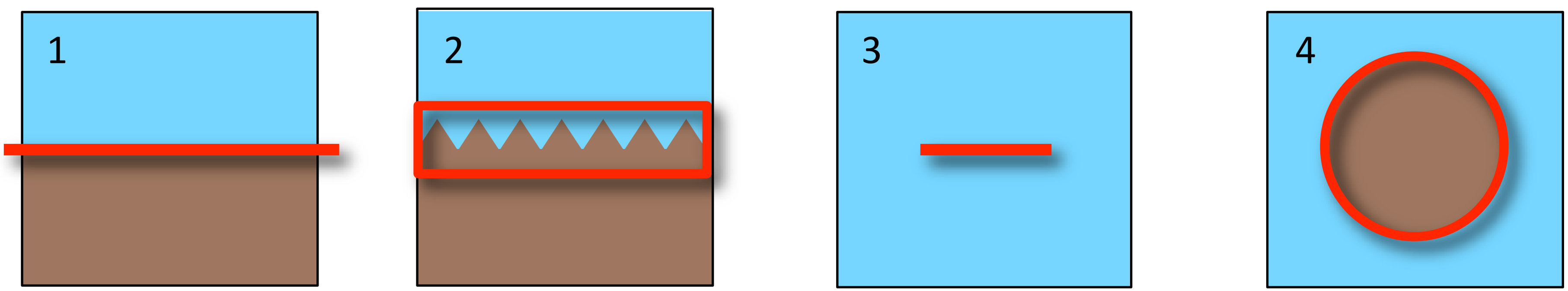


Surface energy balance: why are we interested in the ‘surface’?

- 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

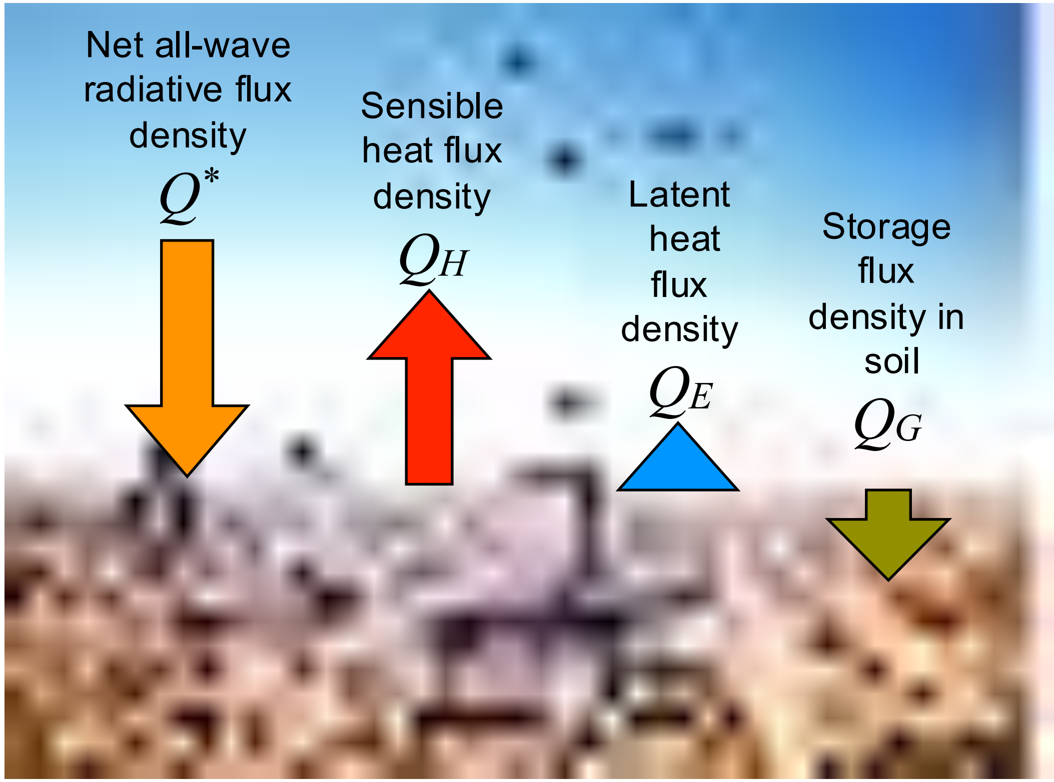
e.g.
forest canopy

e.g.
leaf

e.g.
animal

Energy fluxes at Earth's surface – ideal surface

$$Q^* = Q_H + Q_E + Q_G \;\star$$



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

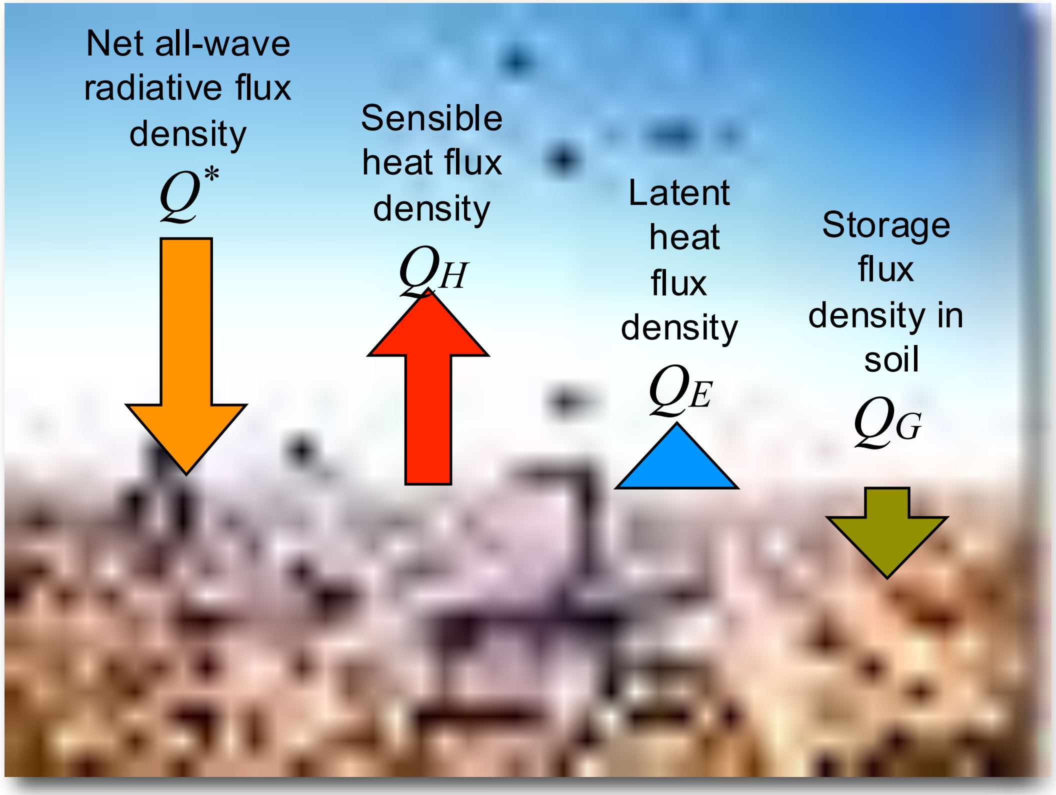
Only vertical fluxes need to be considered.

Sign convention

- All the radiative fluxes directed toward the surface are positive.

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

$$Q^* = Q_H + Q_E + Q_G$$ ★

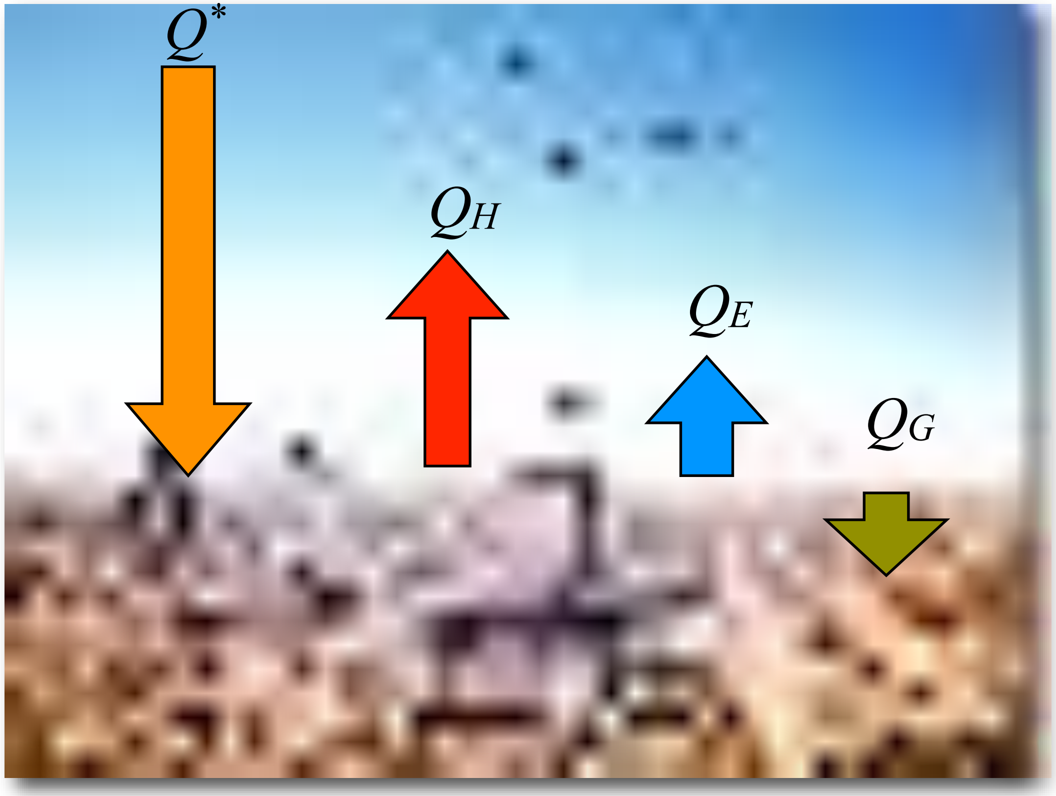


Daytime

Typically:

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

$$Q^* = Q_H + Q_E + Q_G$$ ★



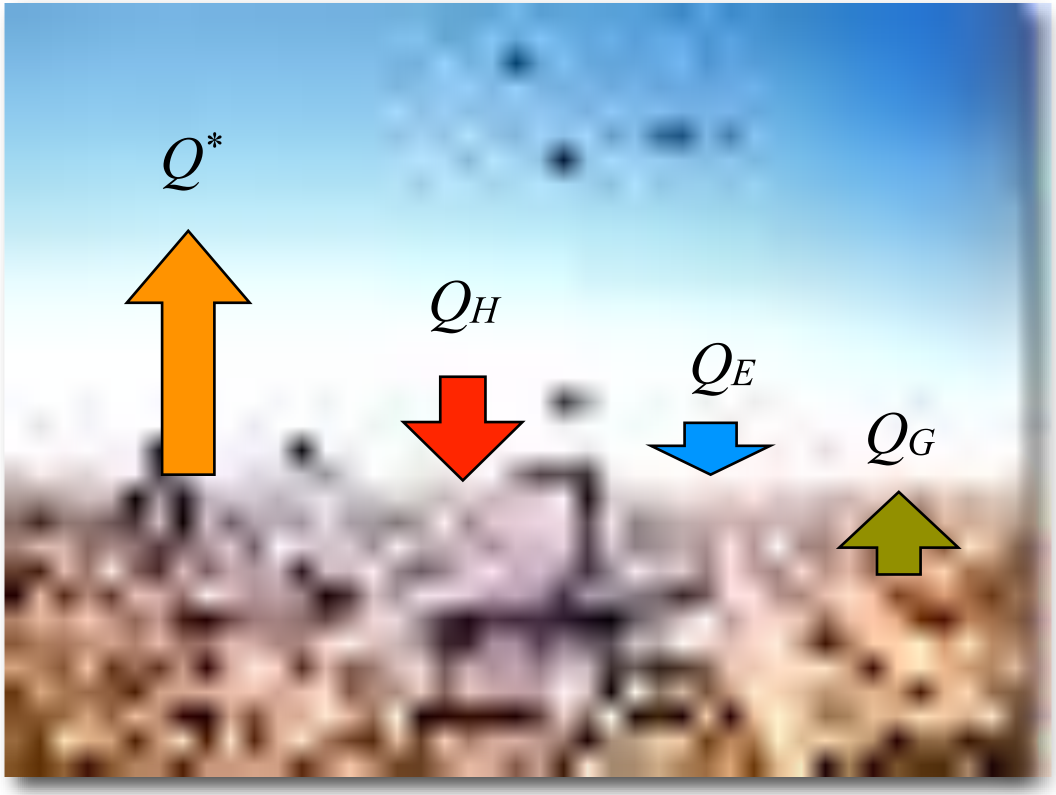
Nighttime

Typically:

- Fluxes are negative

- Fluxes are smaller in magnitude

$$Q^* = Q_H + Q_E + Q_G$$ ★

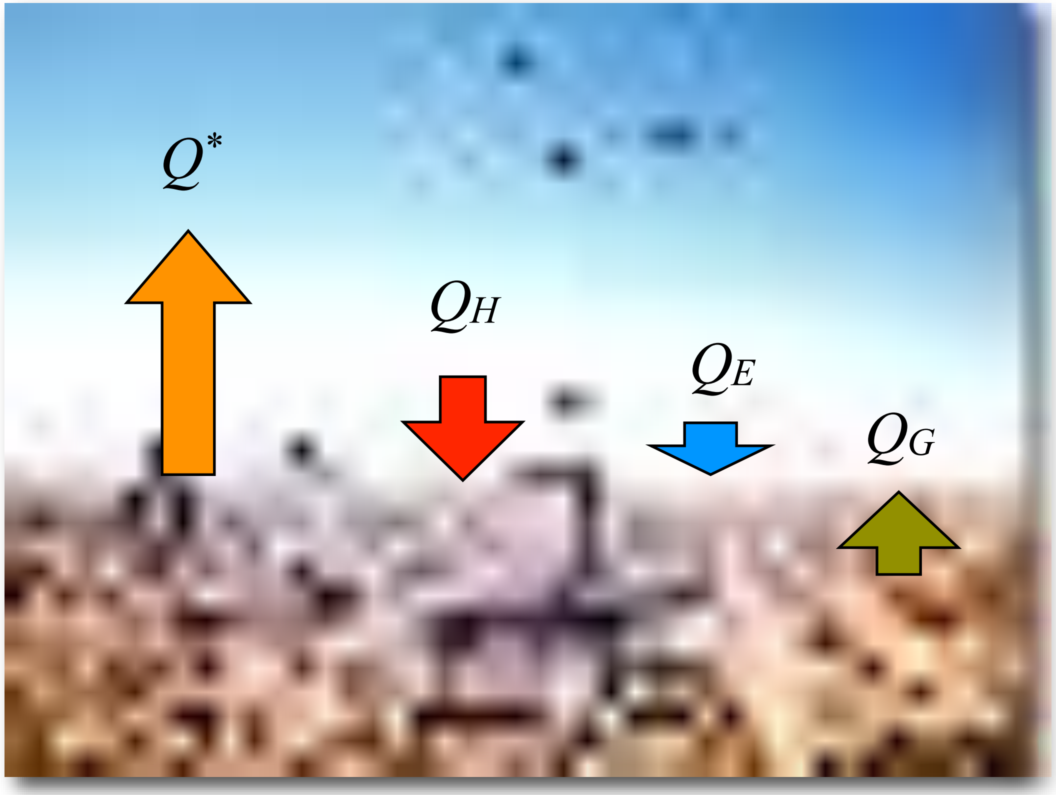


Bowen ratio (B)

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

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

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

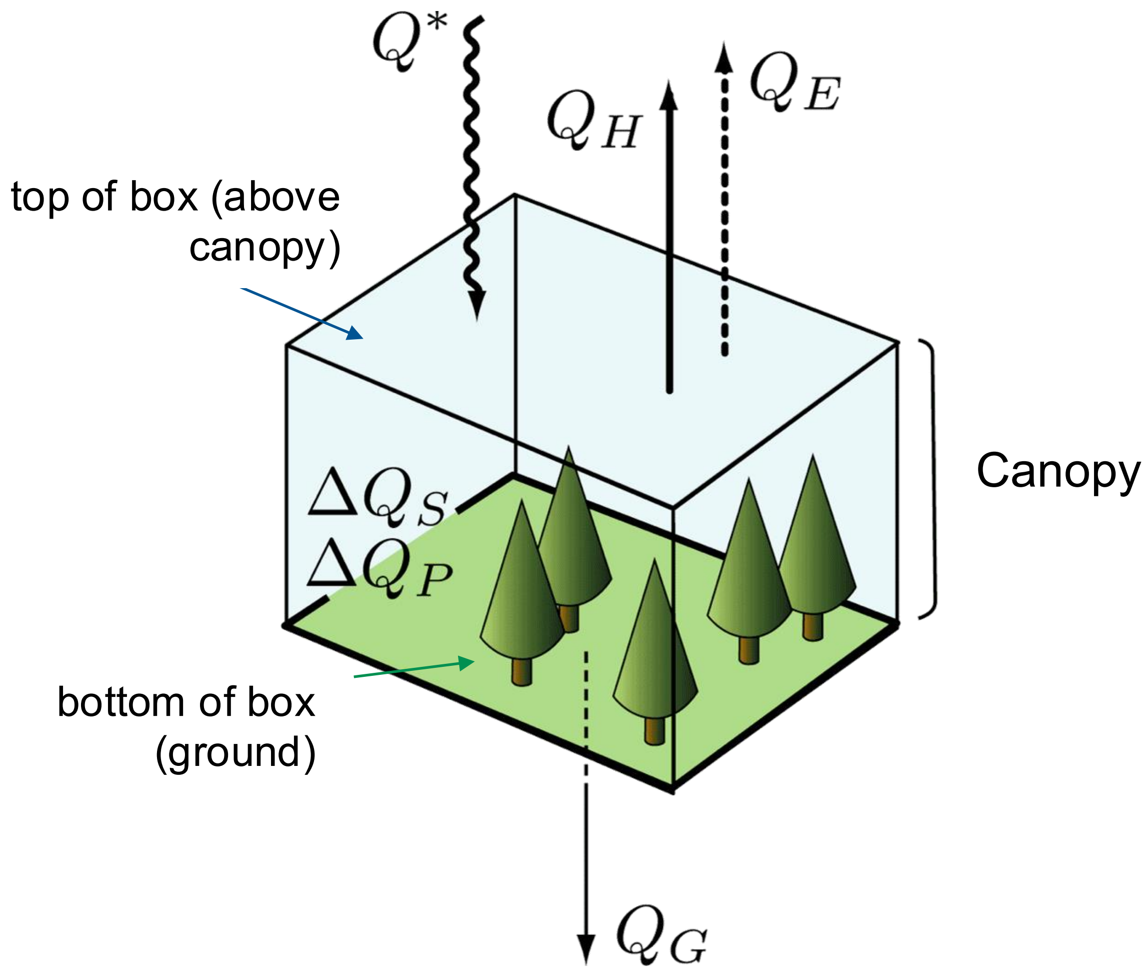


A more complex case

Photo: A. Christen


Photo: A. Christen

Importance of storage terms



Energy balance of a 3-dimensional interface

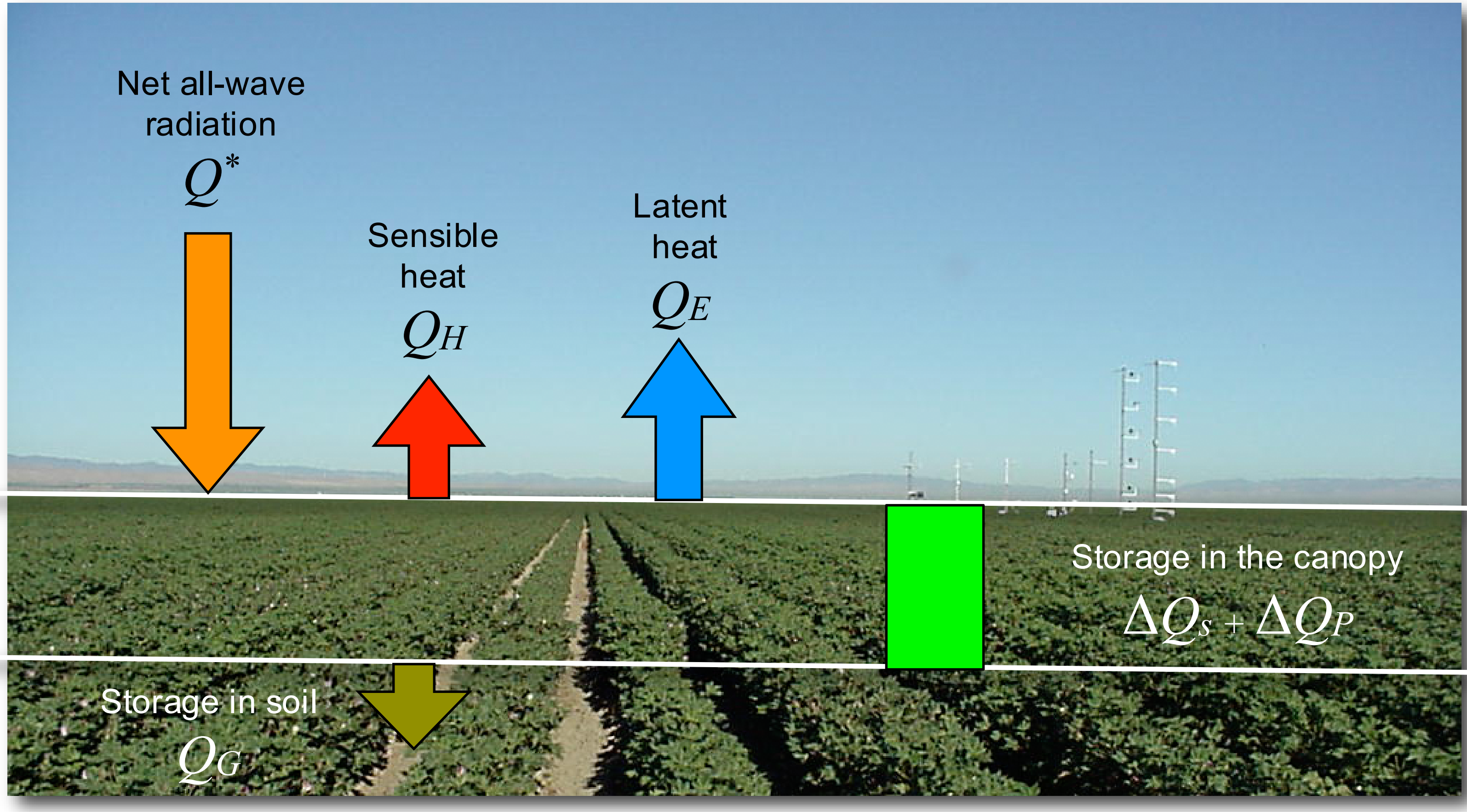


Photo: A. Christen

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.

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			

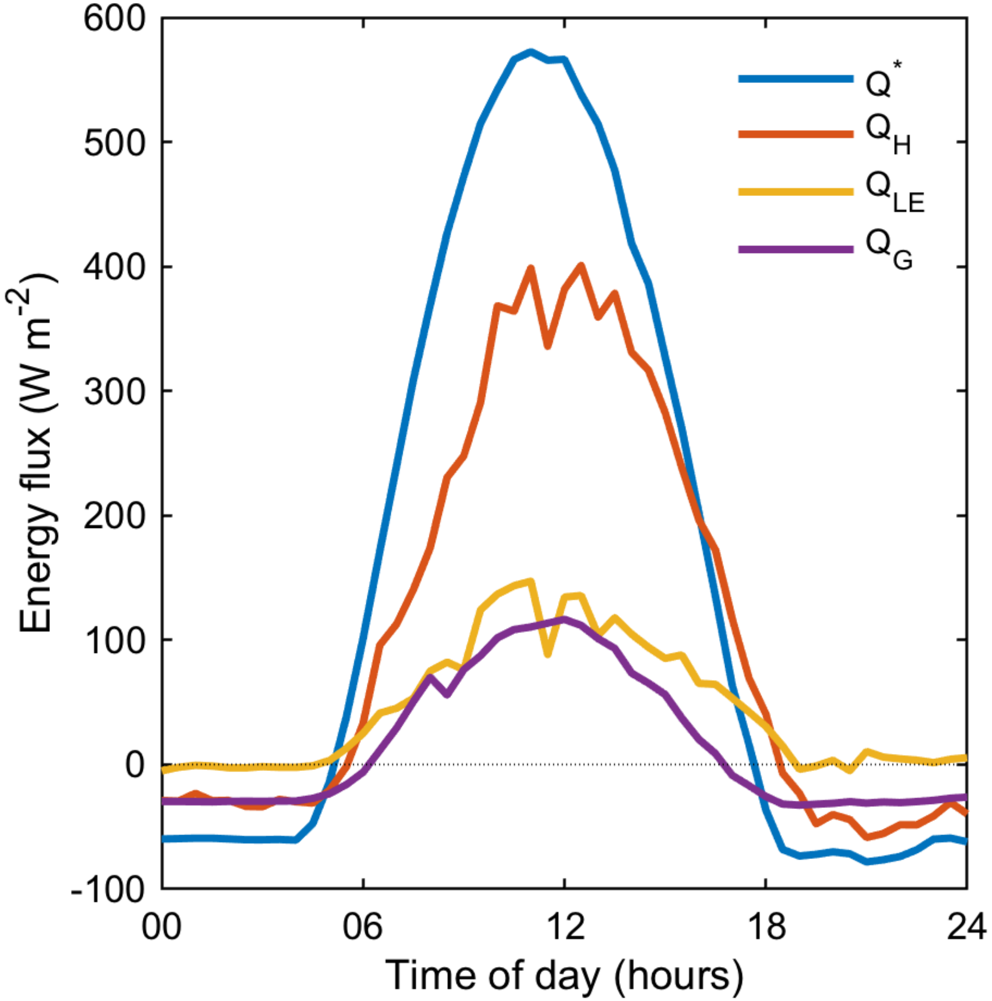
Test your knowledge

Illustrate the typical surface energy balance for:

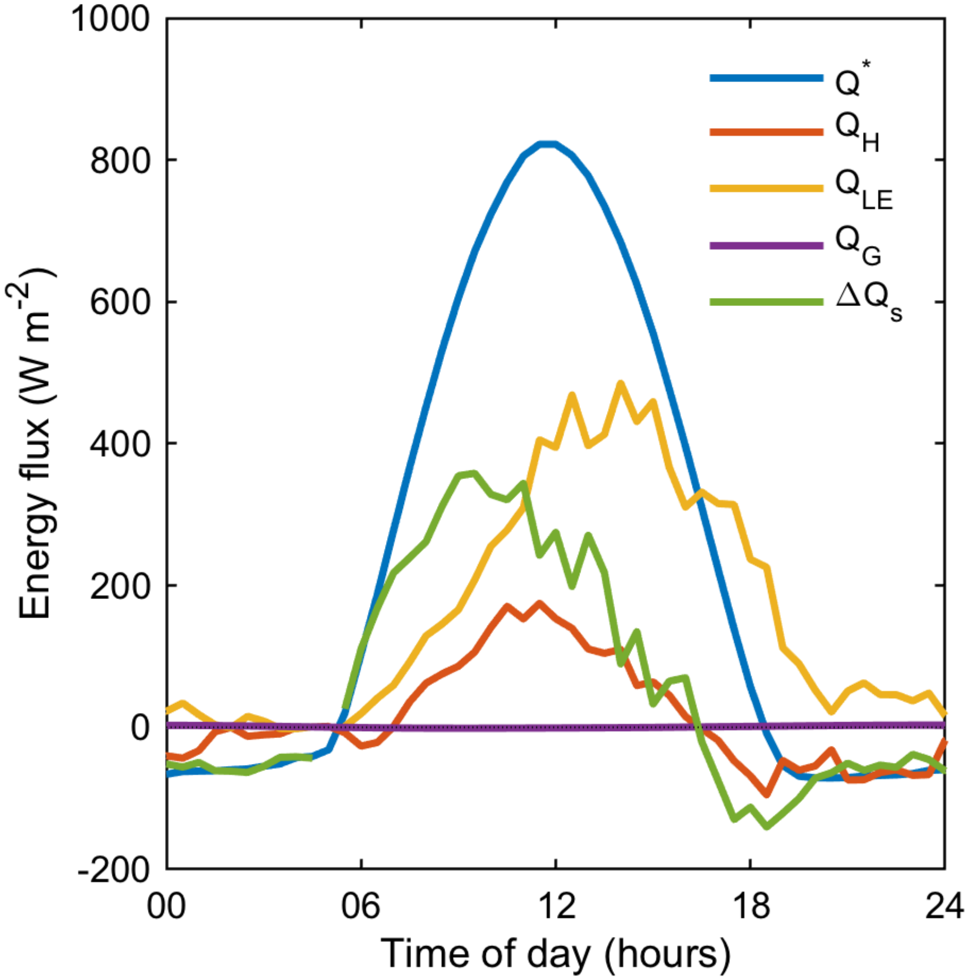
Daytime

Nighttime

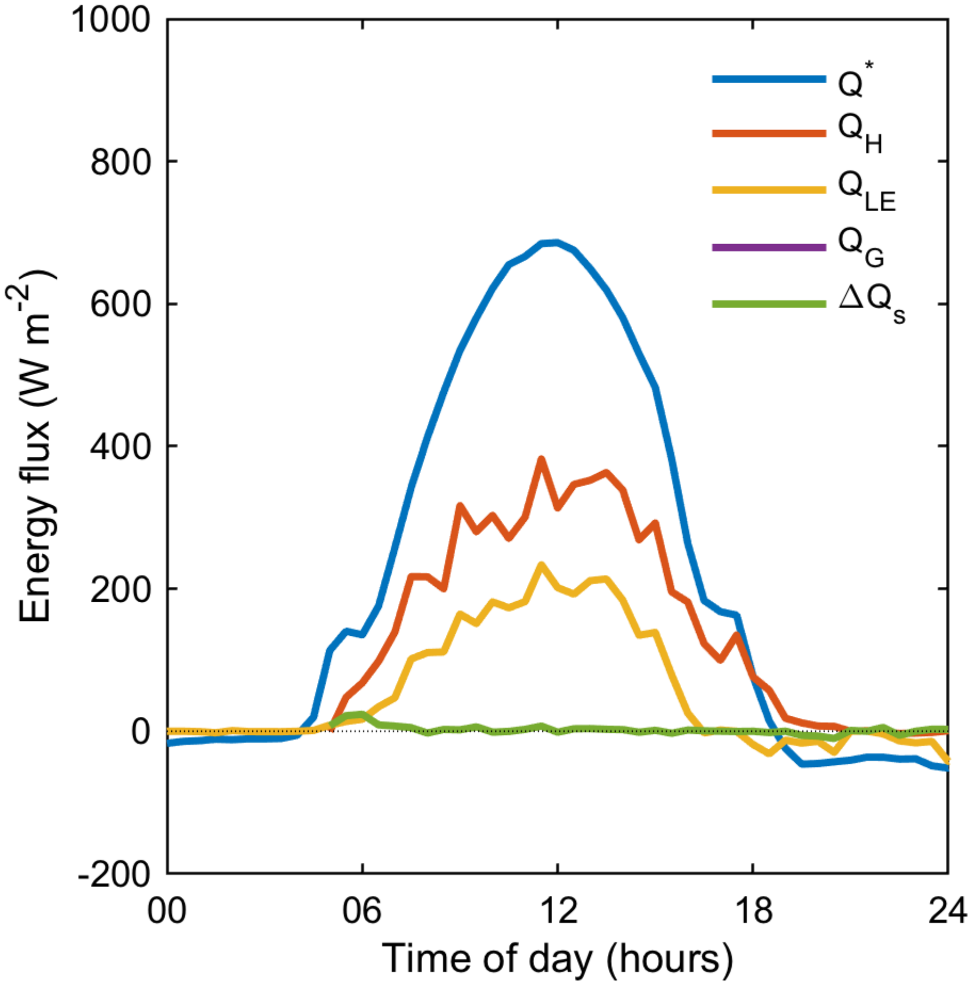
Real world examples: Fallow rice field



Real world examples: Freshwater marsh



Real world examples: Deciduous shrub wetland



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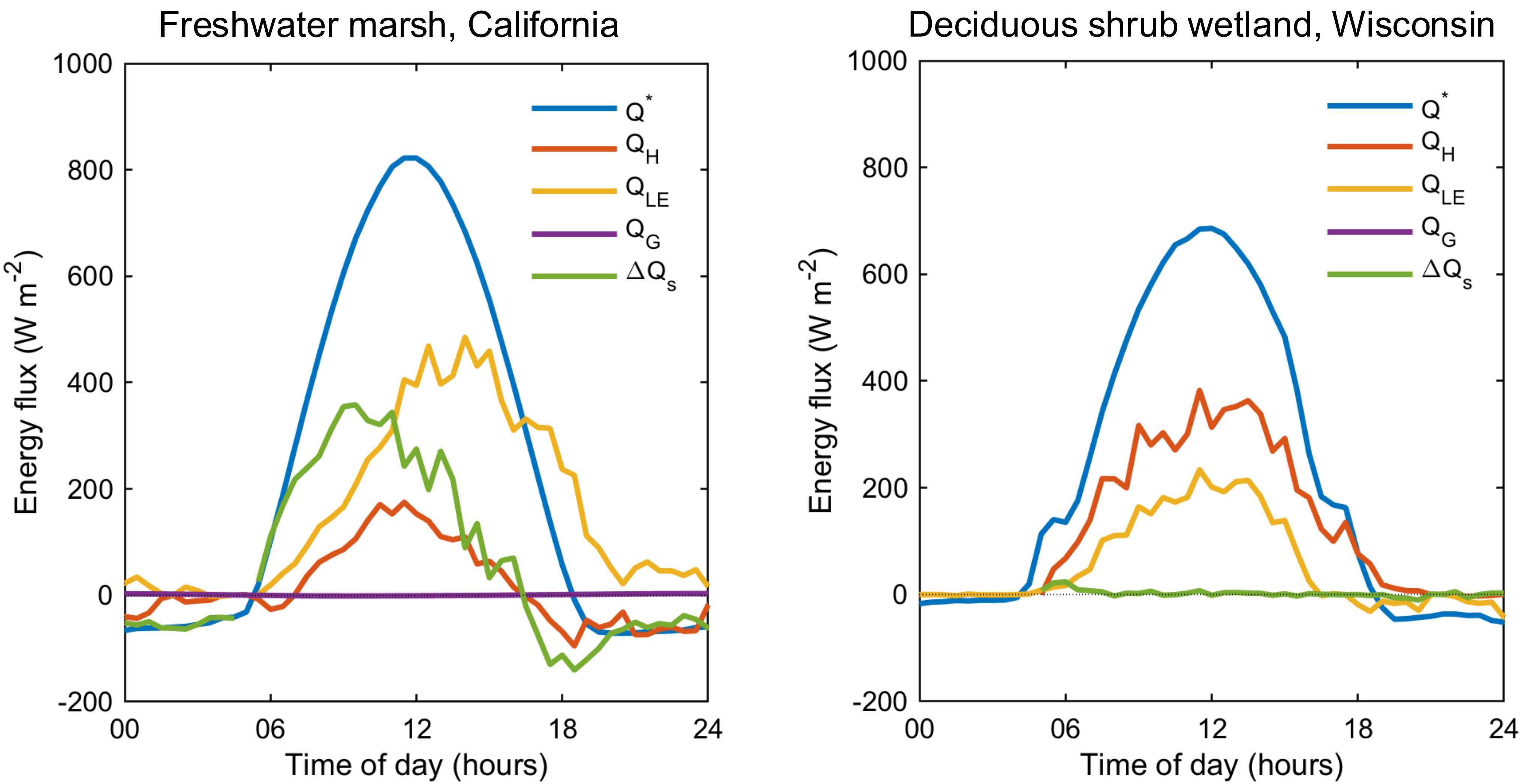
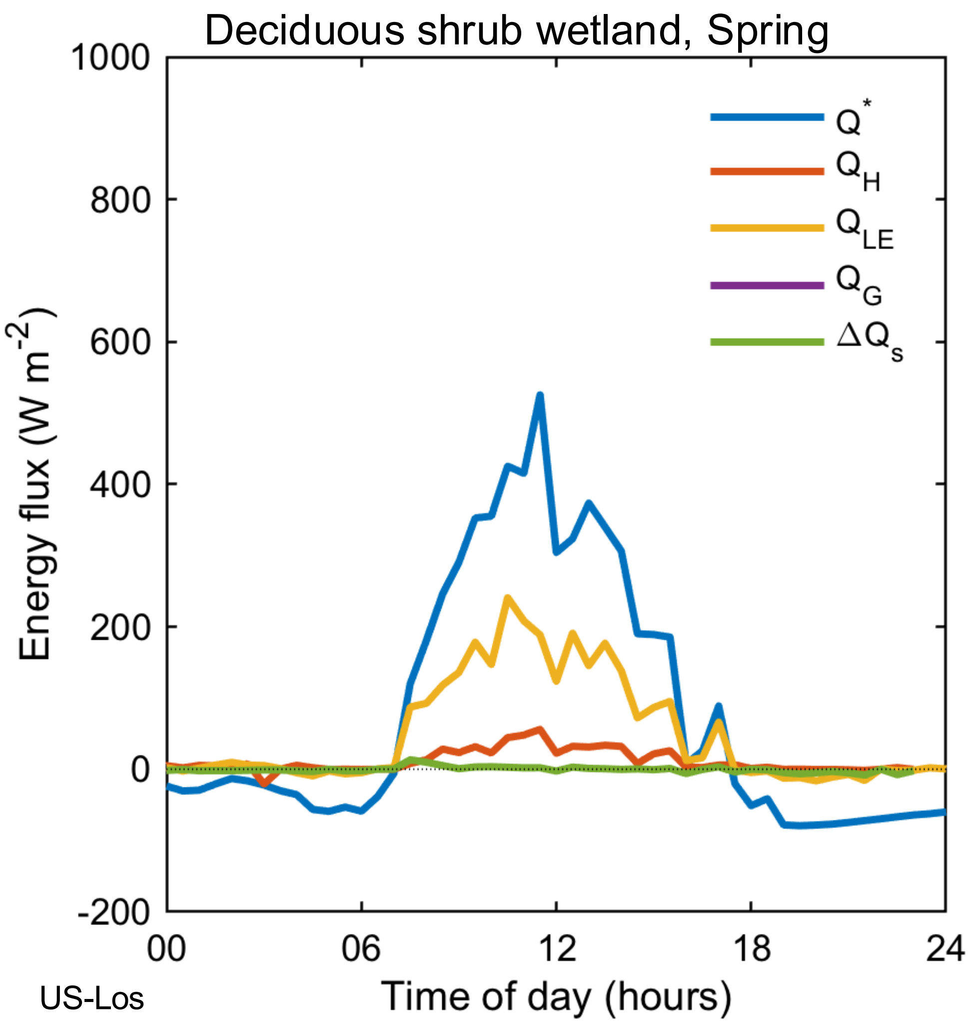
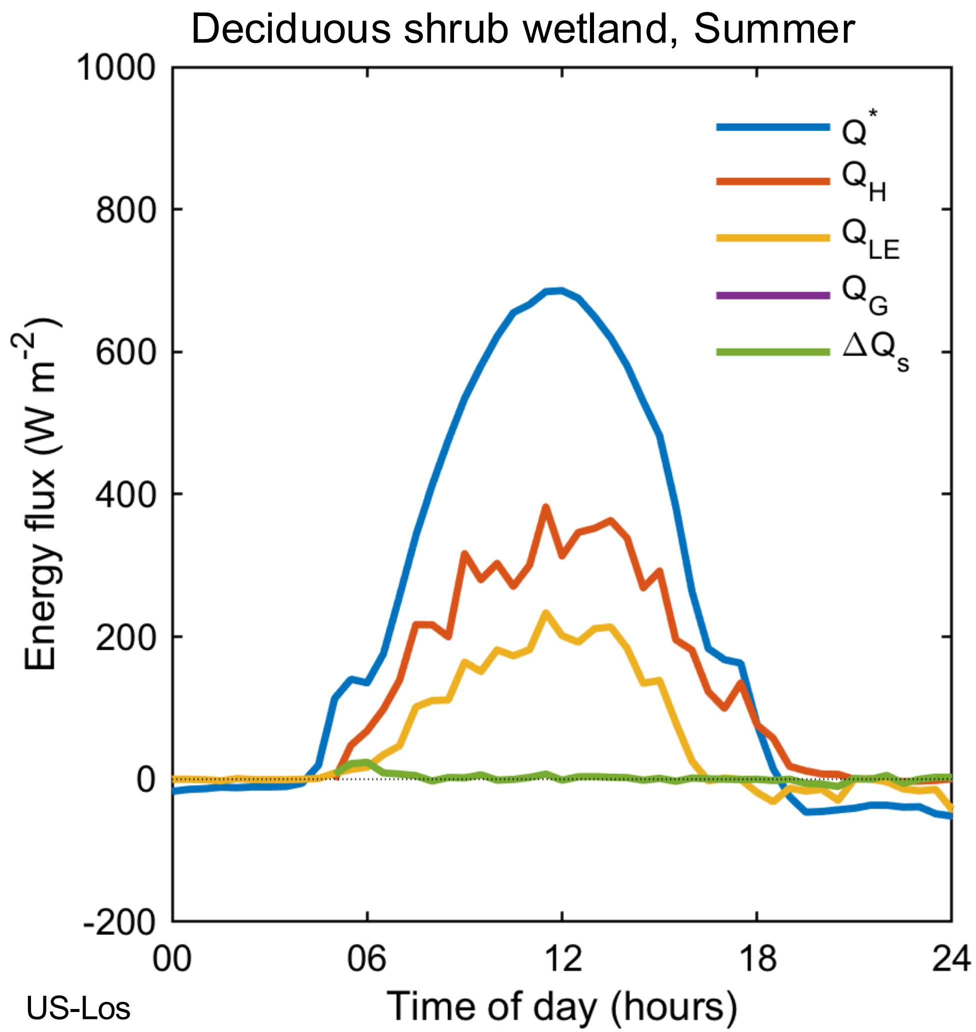
Test your knowledge – Which site has a larger Bowen ratio?

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.

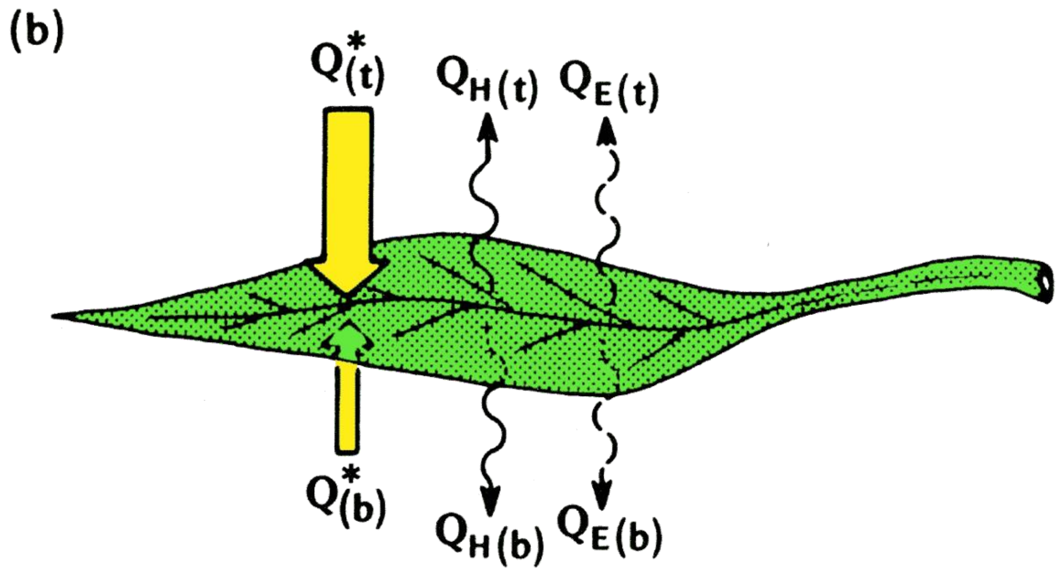


Figure 4.5 Schematic depiction of the fluxes involved in (a) the radiation budget and (b) the energy balance of an isolated leaf.

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.

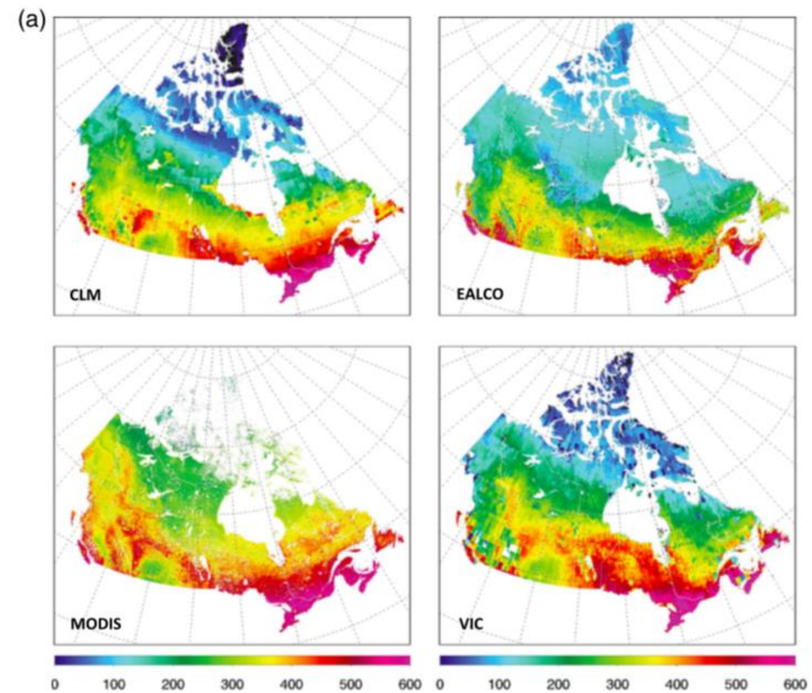
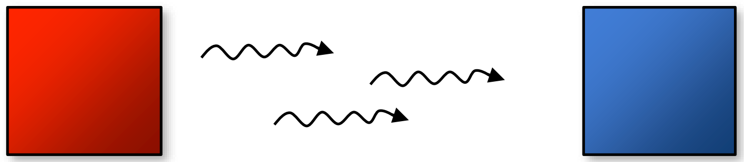


FIG. 3. (a) Mean annual ET (mm yr^{-1}) from CLM, EALCO, MOD16, and VIC. Negative values are in black. MOD16 has 25.5% of the area with no data, primarily in the Arctic. (b) Histogram of mean annual ET (10 mm yr^{-1} bins) from CLM, EALCO, MOD16, and VIC. Note that MOD16 dataset has large gaps over the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

Wang et al. 2015

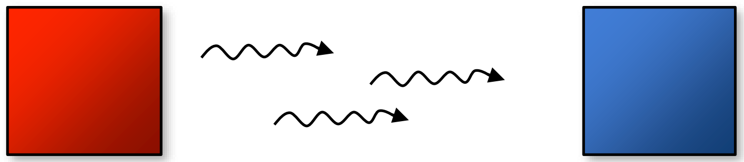
Mechanisms of energy and mass transfer

Radiative exchange - electromagnetic waves, photons

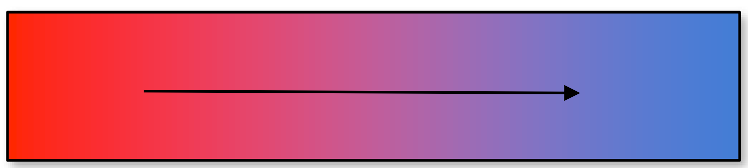


Mechanisms of energy and mass transfer

Radiative exchange - electromagnetic waves, photons

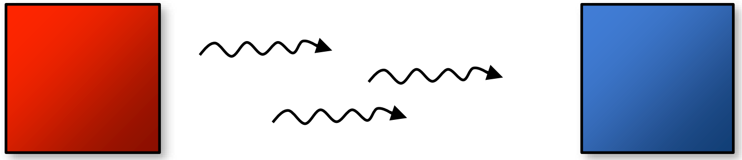


Molecular exchange - conduction and diffusion



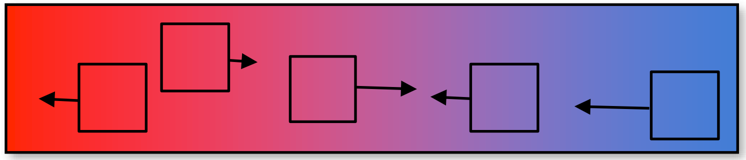
Mechanisms of energy and mass transfer

Radiative exchange - electromagnetic waves, photons

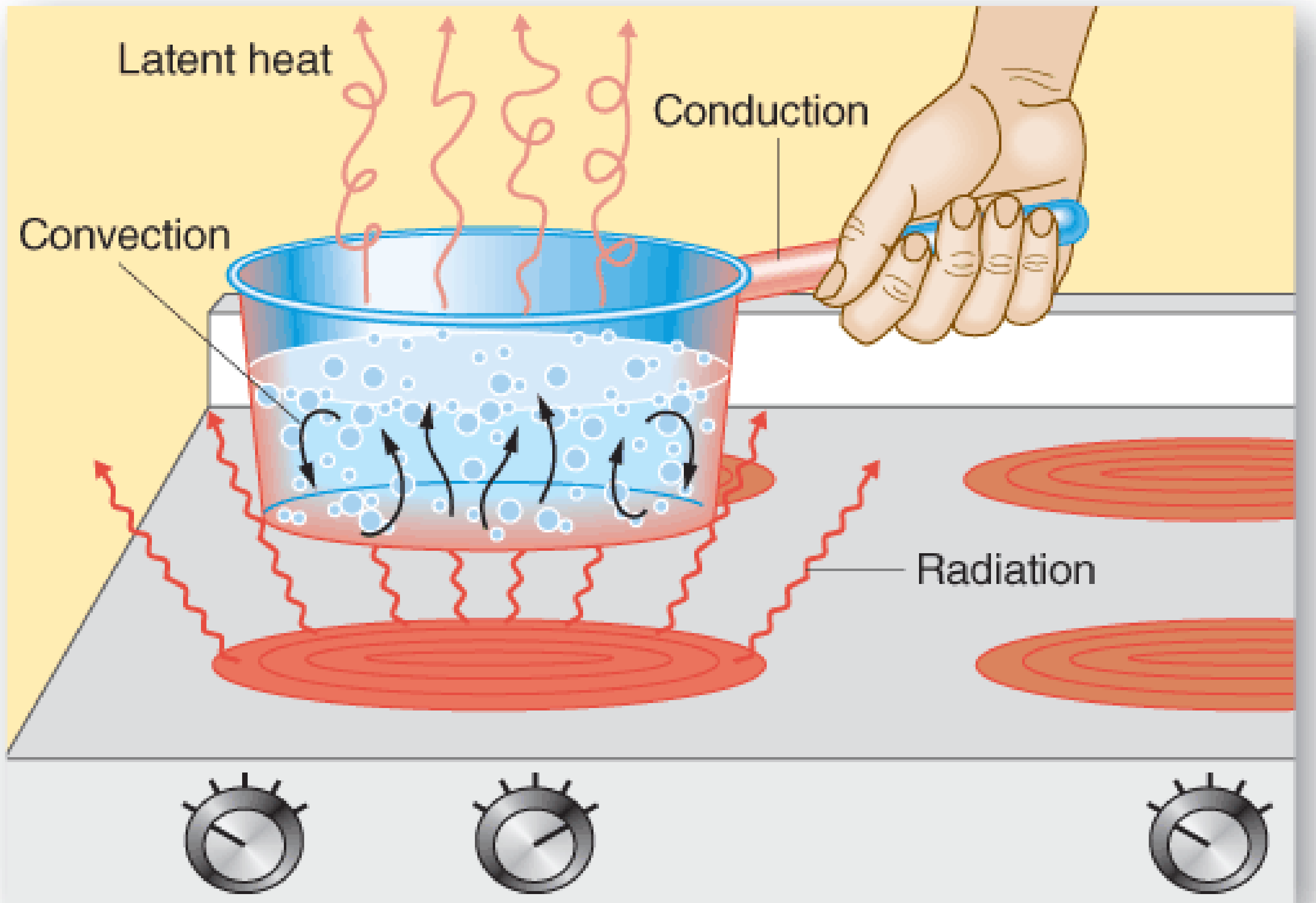


Molecular exchange - conduction and diffusion

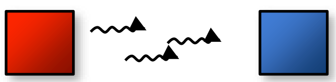
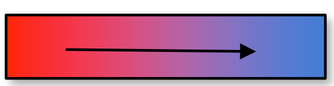
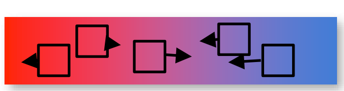
Turbulent exchange - convection in a fluid



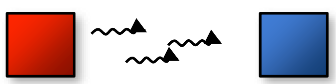
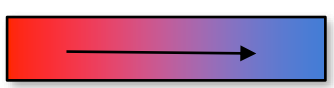
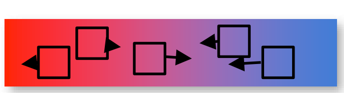
Mechanisms of energy and mass transfer



Transport of energy and mass in the climate system.

	Electromagnetic and -static energy	**Heat** (changes in sensible or latent energy content)	**Mass** (e.g. water vapour)
Radiative exchange 			
Molecular exchange 			
Turbulent exchange 			

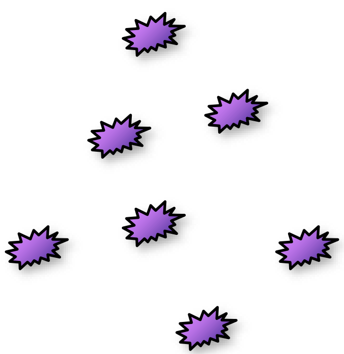
Transport of energy and mass in the climate system.

	Electromagnetic and -static energy	**Heat** (changes in sensible or latent energy content)	**Mass** (e.g. water vapour)
Radiative exchange 	**Shortwave, Longwave, Net all-wave-radiation**		
Molecular exchange 	Electricity conduction (not relevant in the atmosphere)	**Heat conduction**	**Diffusion of water vapour molecules**
Turbulent exchange 	Turbulent exchange of charged gases (thunderstorms)	**Turbulent sensible heat flux density**	**Turbulent latent heat flux density**

Quantifying transfer - Fluxes and flux densities

Energy

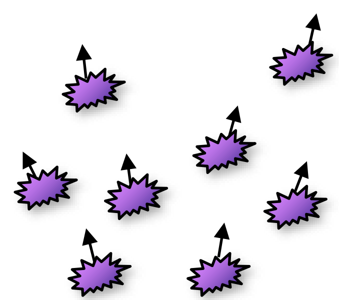
Equivalence between energy and heat



J

Power, heat flux

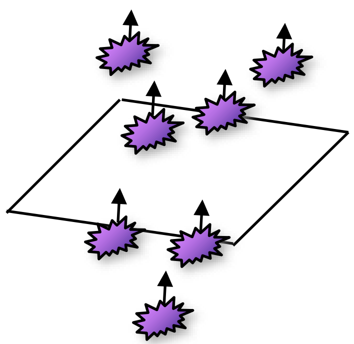
is rate of work or the flow rate of energy



W
=
$J\ s^{-1}$

Heat flux density

is flow rate of energy per unit (surface) area

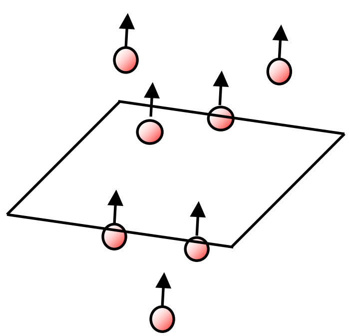


$W\ m^{-2}$
=
$J\ s^{-1}\ m^{-2}$

Flux densities of mass, heat and radiant energy

Mass flux density

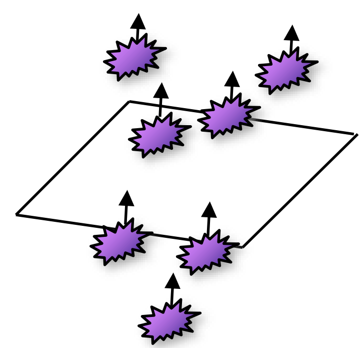
is flow rate of mass per unit (surface) area



kg s^{-1} m^{-2}

Heat flux density

is flow rate of latent or sensible heat per unit (surface) area



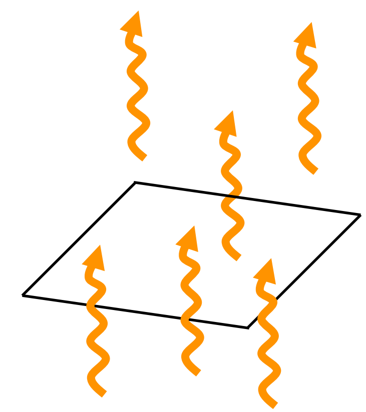
W m^{-2}

=

J s^{-1} m^{-2}

Radiant flux density

is flow rate of radiative energy per unit (surface) area



W m^{-2}

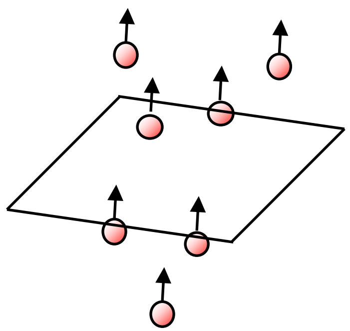
=

J s^{-1} m^{-2}

Energy fluxes at Earth's surface

Mass flux density

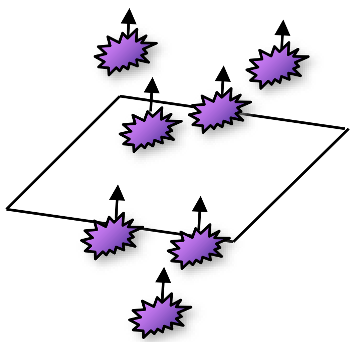
is flow rate of mass per unit (surface) area



$kg\ s^{-1}\ m^{-2}$

Heat flux density

is flow rate of latent or sensible heat per unit (surface) area



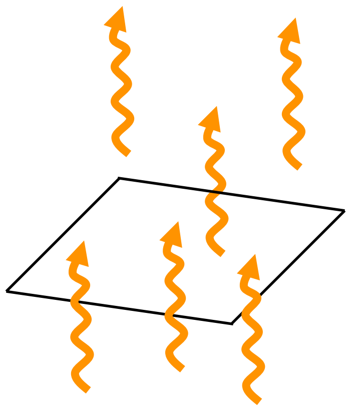
$W\ m^{-2}$

=

$J\ s^{-1}\ m^{-2}$

Radiant flux density

is flow rate of radiative energy per unit (surface) area



$W\ m^{-2}$

=

$J\ s^{-1}\ m^{-2}$

Take home points (1/2)

- We discussed the **conservation of energy and mass** as a powerful principle to describe exchange in the atmosphere.
- We saw that over **flat and homogeneous terrain we simplify situations** to a horizontally homogeneous case i.e. where the mean horizontal gradients vanish.
- 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.

Take home points (2/2)

- 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.
- Transfer of mass and energy (heat and radiant energy) can be quantified using **flux densities**, where transfer is normalized per unit area and unit time.