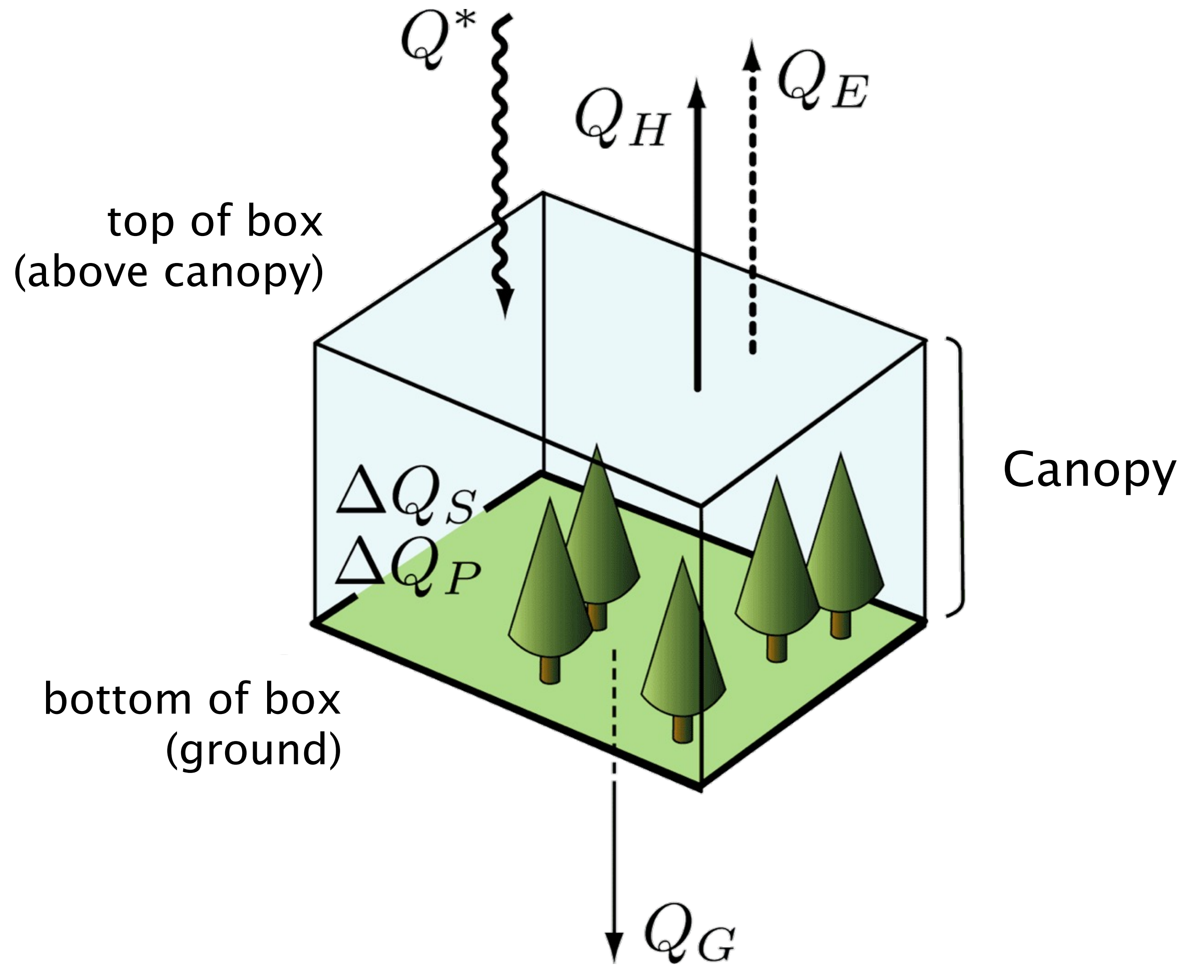

Q^*
Q_H
Q_E
top of box
(above canopy)
Canopy
ΔQ_S
ΔQ_P
bottom of box
(ground)
Q_G

Today’s 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.
- Review: Define the dominant energy and mass transfer mechanisms in the atmosphere.

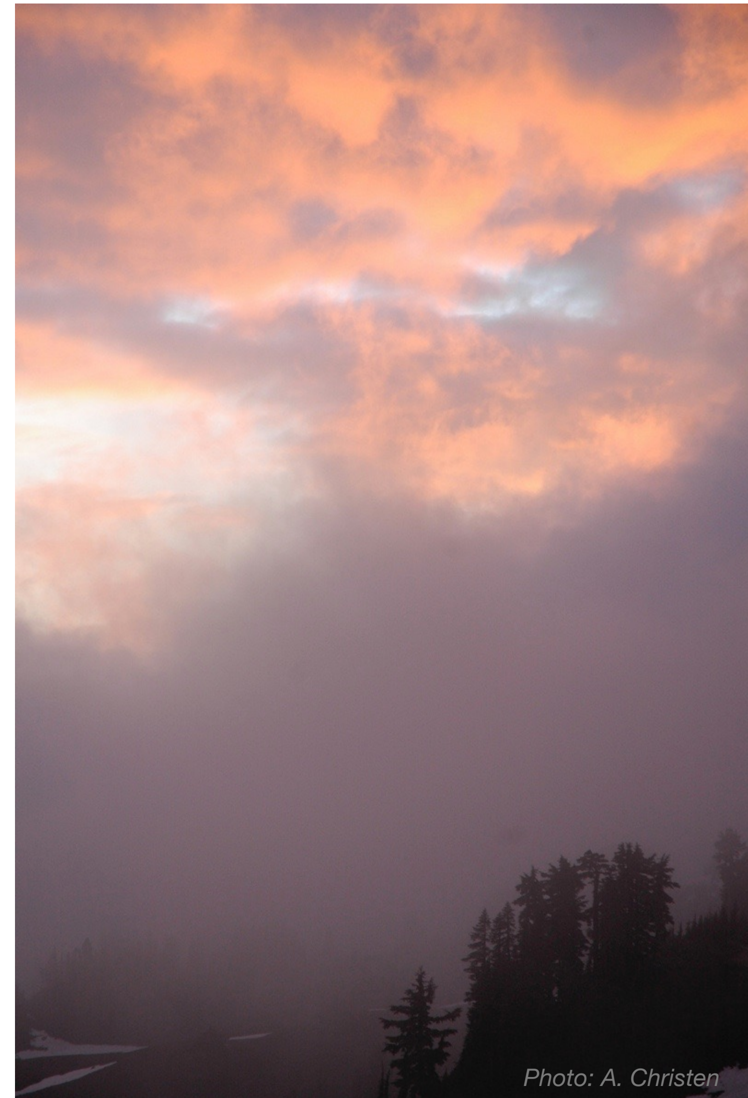


Photo: A. Christen

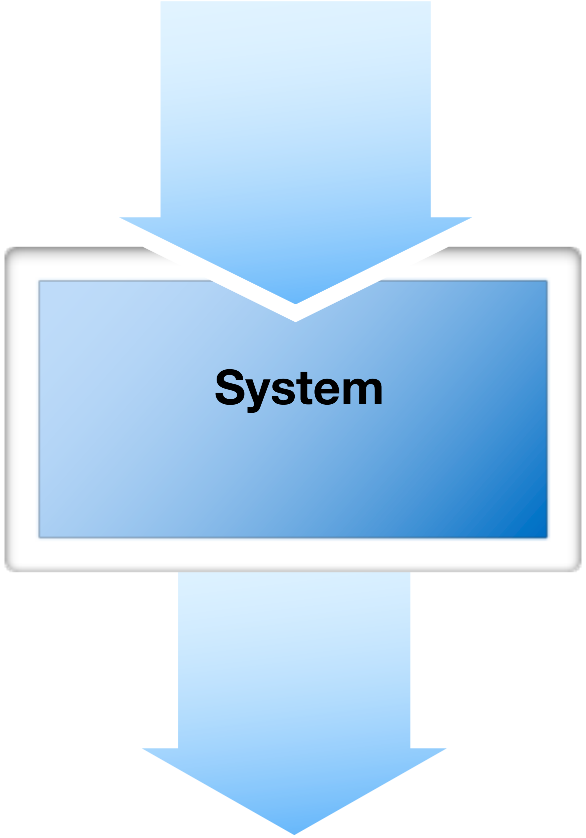
Conservation of energy and mass

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

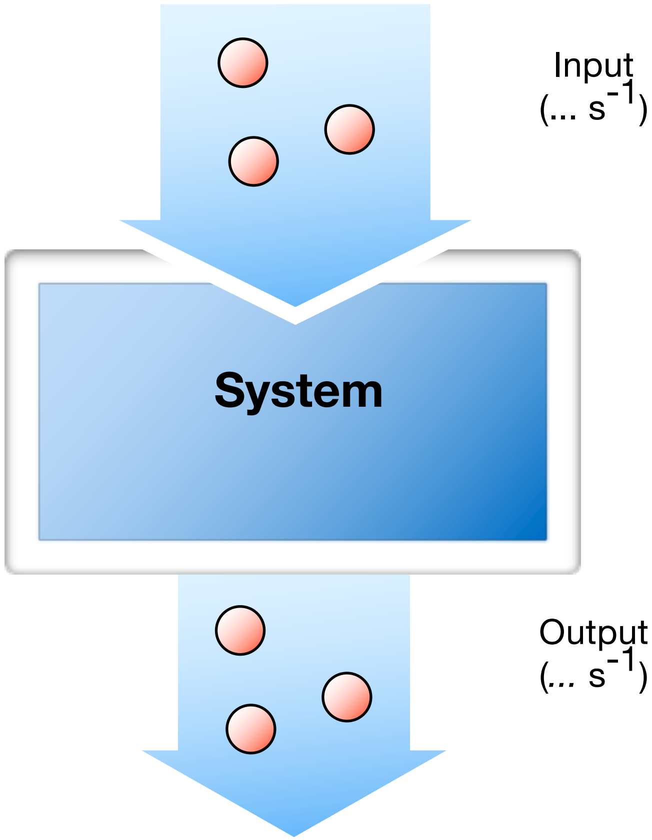
Neither mass nor energy can be created or destroyed by any ordinary means. We can convert energy from one form to another and move it around.

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

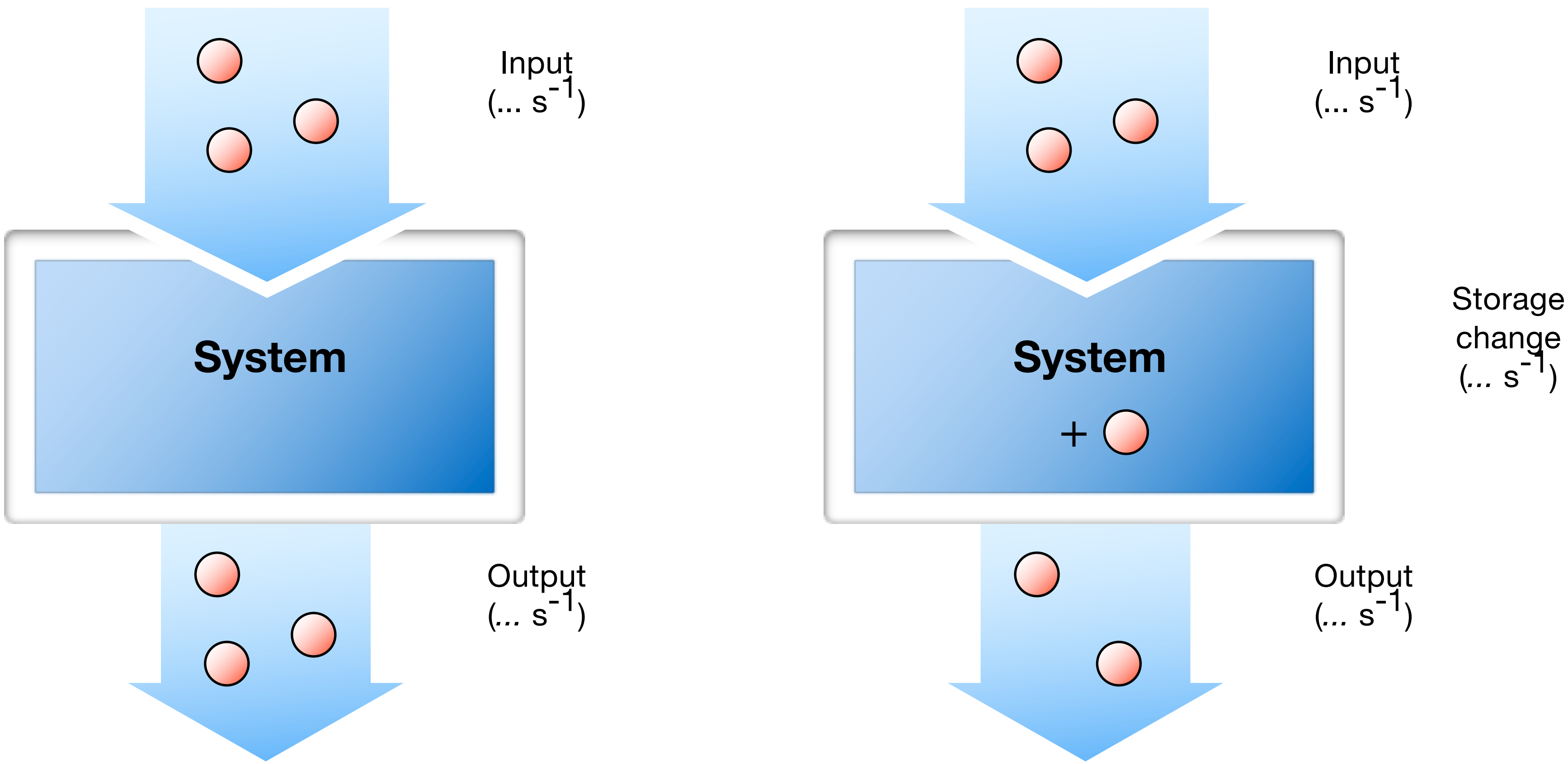


Input = Output



Input - Output = 0

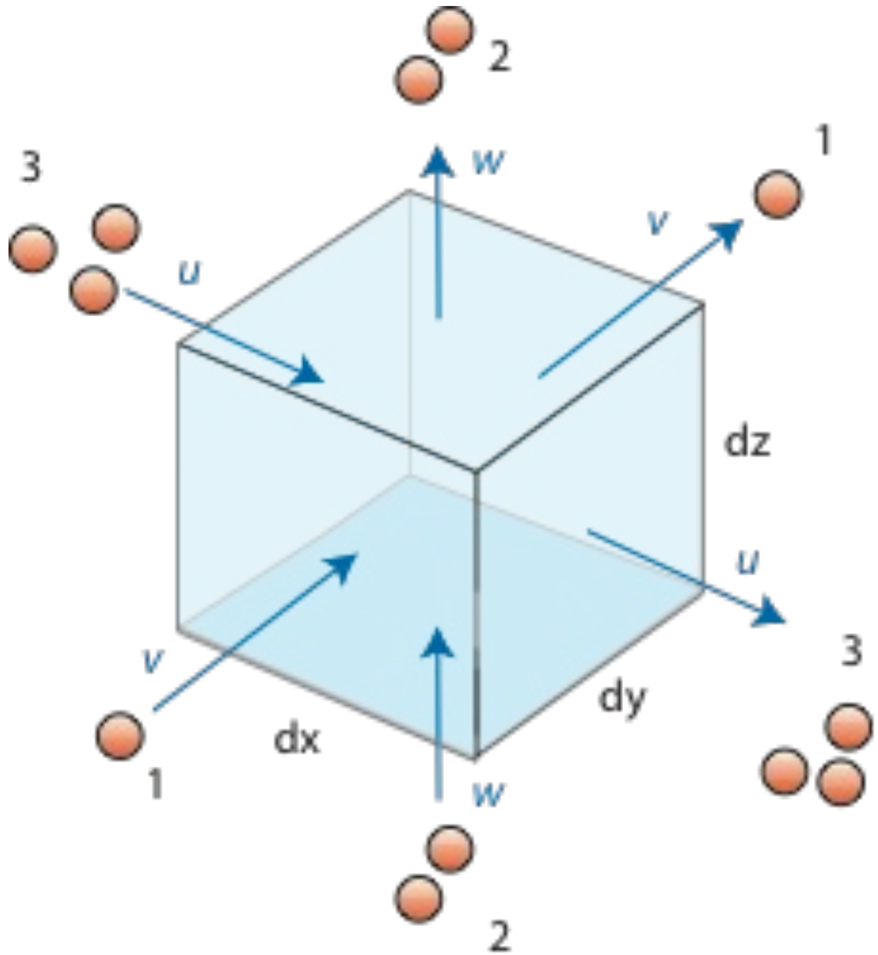
Input – Output = Storage change



Input - Output = 0

Input - Output = Storage change

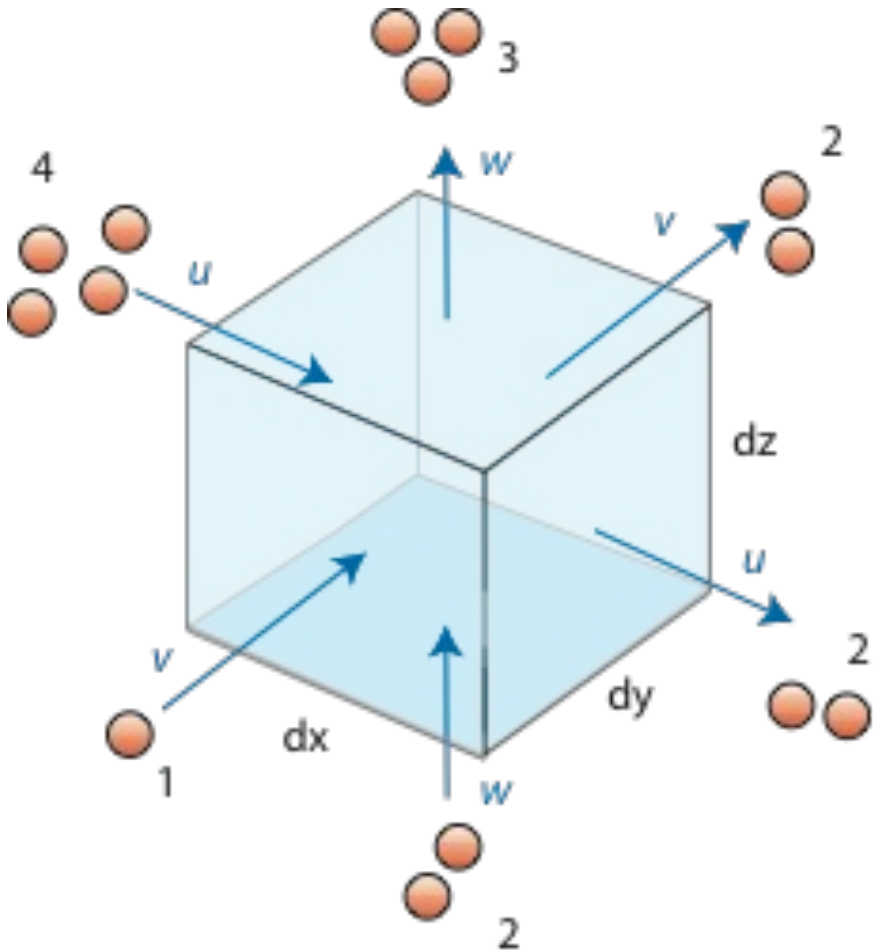
Conservation in a three-dimensional box



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

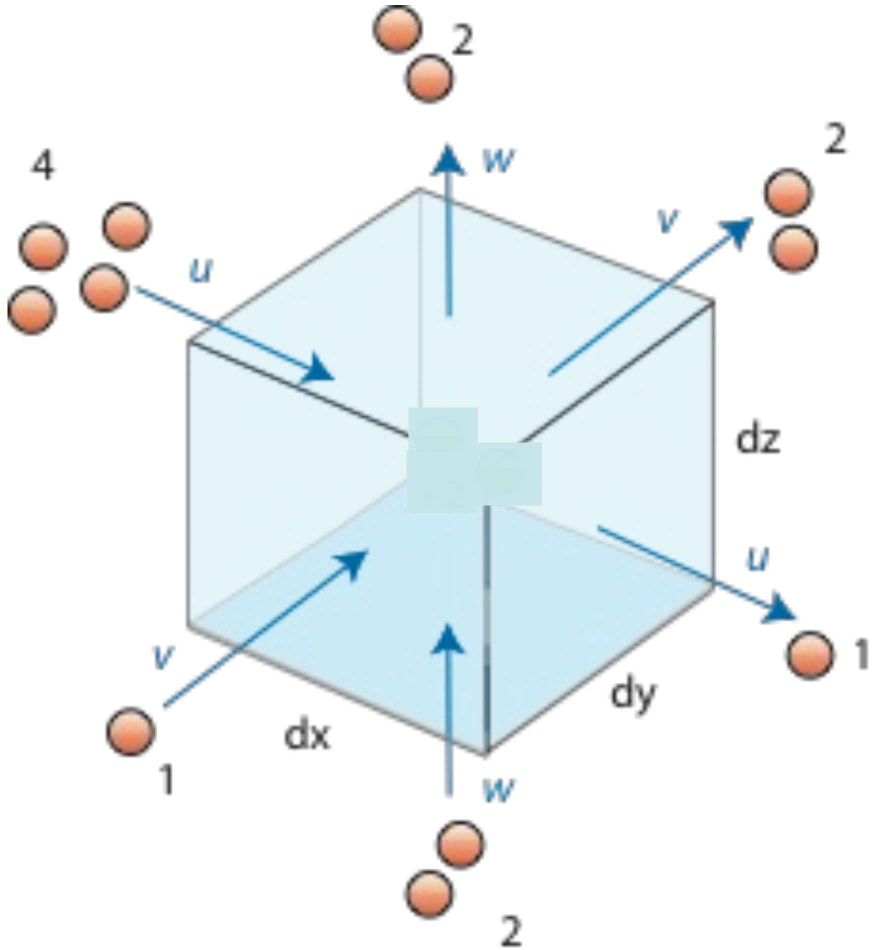
divergence free case

What is the change in storage? (Slido question)



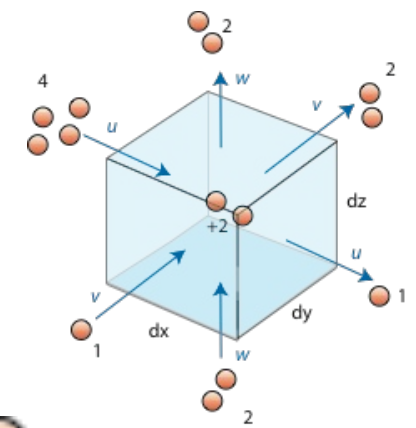
input output storage

What is the change in storage in this case? (Slido Question)



input output storage

Conservation of a scalar in three dimensions



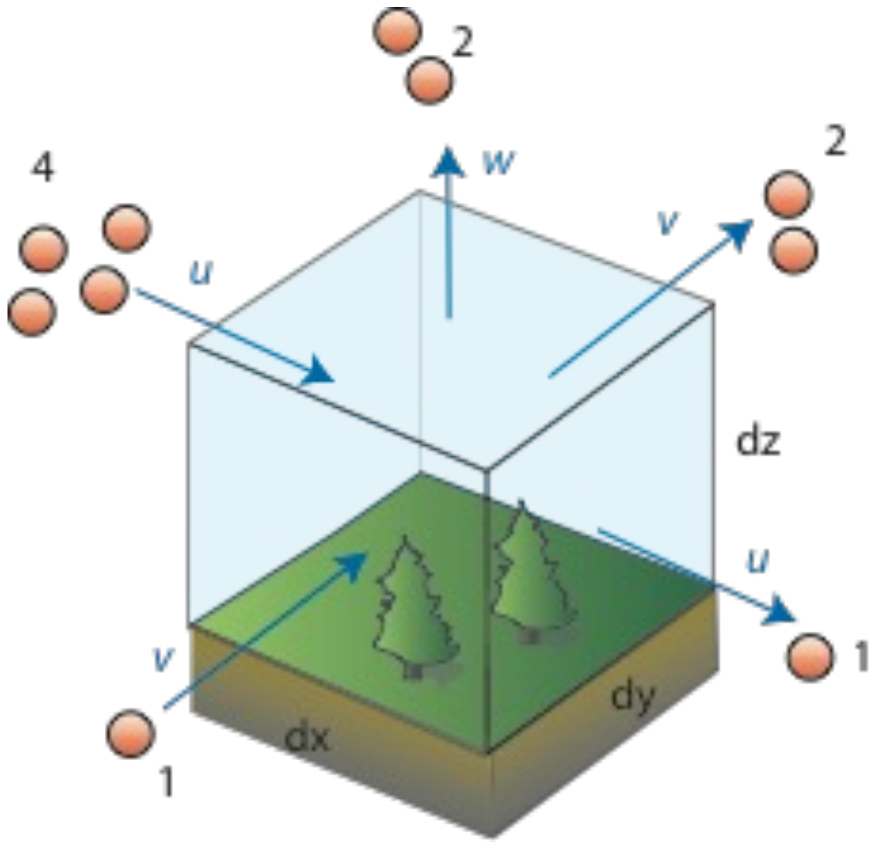
total derivative
(change in entire system)

partial derivatives
(changes in time or space)

$$\frac{d\bigcirc}{dt} = \frac{\partial\bigcirc}{\partial t} + \underbrace{u\frac{\partial\bigcirc}{\partial x} + v\frac{\partial\bigcirc}{\partial y} + w\frac{\partial\bigcirc}{\partial z}}_{\text{Advection (input / output by wind)}}$$

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>:

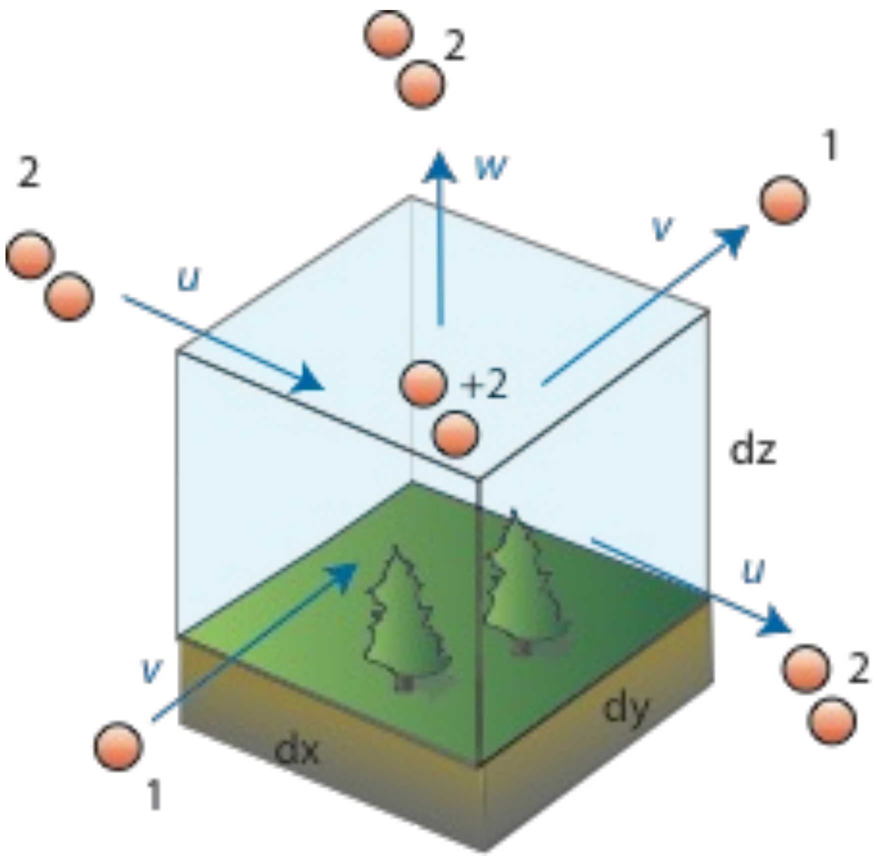
overbar means average over a longer time
(e.g. an hour to avoid turbulent variations)

$$\frac{\partial \overline{\bullet}}{\partial x} \text{ and } \frac{\partial \overline{\bullet}}{\partial y} \ll \frac{\partial \overline{\bullet}}{\partial z}$$ (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:

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

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**

Study questions - conservation equation for humidity

$$0 = \frac{\partial \rho_v}{\partial t} + u\frac{\partial \rho_v}{\partial x} + v\frac{\partial \rho_v}{\partial y} + w\frac{\partial \rho_v}{\partial z}$$

where is ρ_v vapour density (same as absolute humidity). For the purpose of this set of questions, we assume there is no condensation or vaporization happening.

Study questions - conservation equation for humidity

$$\overset{\text{(i)}}{0 = \boxed{\frac{\partial \rho_v}{\partial t}}} + u\frac{\partial \rho_v}{\partial x} + v\frac{\partial \rho_v}{\partial y} + w\frac{\partial \rho_v}{\partial z}$$

1. What does (i) describe? Units of the term?

Study questions - conservation equation for humidity

$$0 = \underbrace{\frac{\partial \rho_v}{\partial t}}_{\text{(i)}} + \underbrace{\boxed{u\frac{\partial \rho_v}{\partial x}}}_{\text{(ii)}} + v\frac{\partial \rho_v}{\partial y} + w\frac{\partial \rho_v}{\partial z}$$

2. What does (ii) describes? Units?

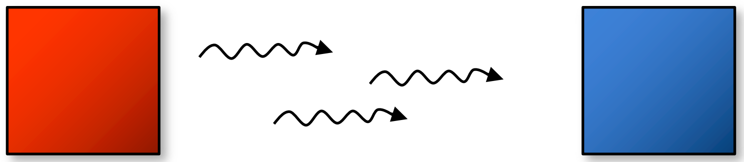
Study questions - conservation equation for humidity

$$0 = \frac{\partial \rho_v}{\partial t} + u\frac{\partial \rho_v}{\partial x} + v\frac{\partial \rho_v}{\partial y} + w\frac{\partial \rho_v}{\partial z}$$

3. Assume **horizontal homogeneous conditions**, and $\frac{\partial \rho_v}{\partial z}$ = -1 g m^{-3} m^{-1}, u = 2 m s^{-1}, v = 0 m s^{-1}, w = 0.1 m s^{-1}. Is the air drying out, becoming more humid, or is the humidity staying constant?

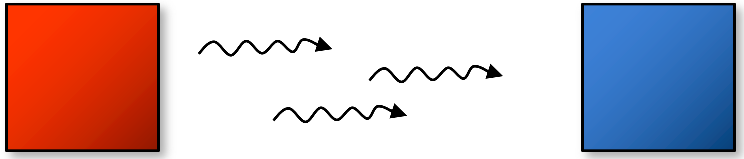
Mechanisms of energy and mass transfer

Radiative exchange - electromagnetic waves, photons



Mechanisms of energy and mass transfer

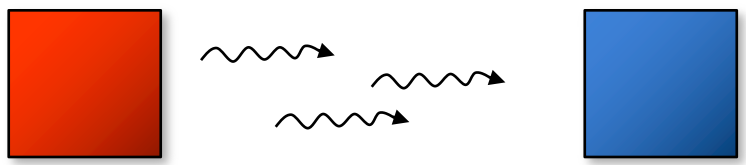
Radiative exchange - electromagnetic waves, photons



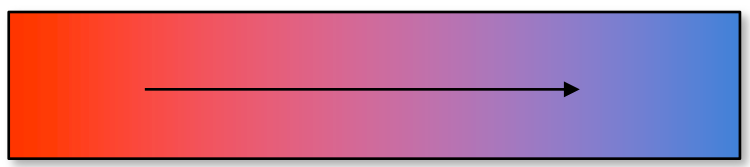
Molecular exchange - conduction and diffusion

Mechanisms of energy and mass transfer

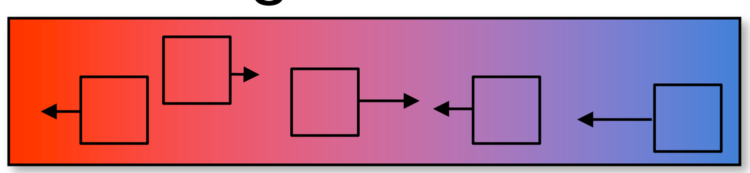
Radiative exchange - electromagnetic waves, photons



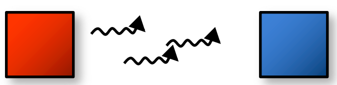
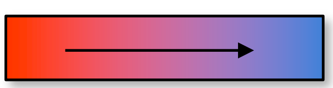
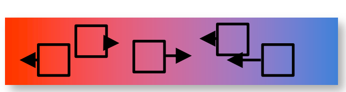
Molecular exchange - conduction and diffusion



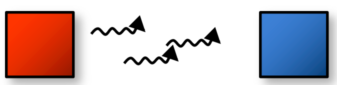
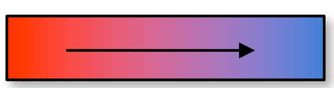
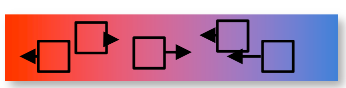
Turbulent exchange - convection in a fluid



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 			

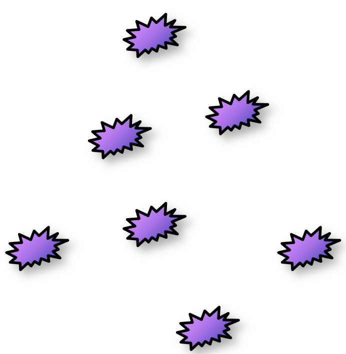
Transport of energy and mass in the climate system.

	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

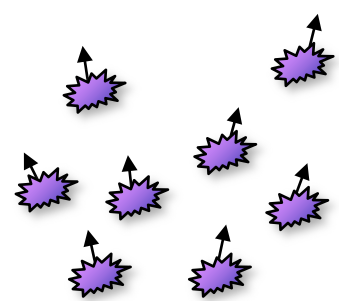
Equivalence between energy and heat



J

Power, heat flux

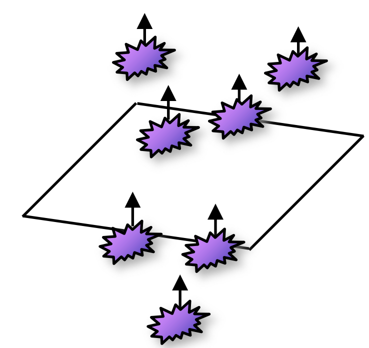
is rate of work or the flow rate of energy



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

Heat flux density

is flow rate of energy per unit (surface) area

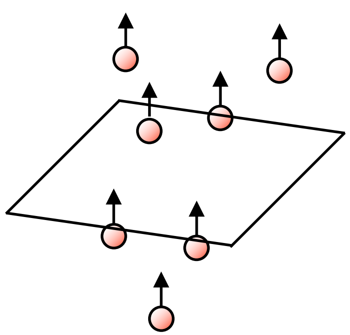


$W\ m^{-2}$
=
$J\ s^{-1}\ m^{-2}$

Flux densities of mass, heat and radiant energy

Mass flux density

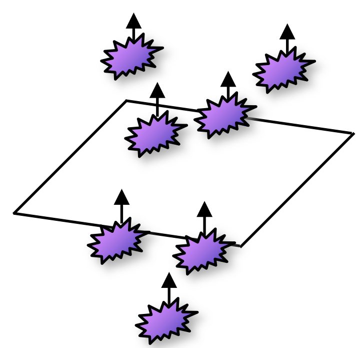
is flow rate of mass per unit (surface) area



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

Heat flux density

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



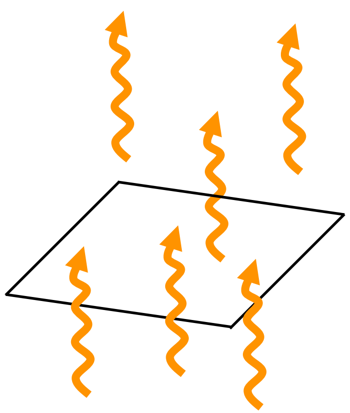
W m^{-2}

=

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

Radiant flux density

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



W m^{-2}

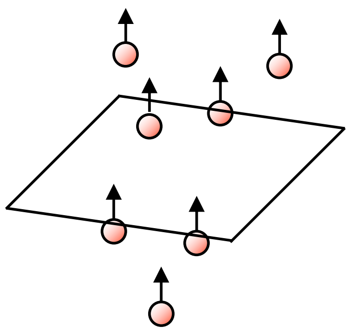
=

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

Energy fluxes at Earth's surface

Mass flux density

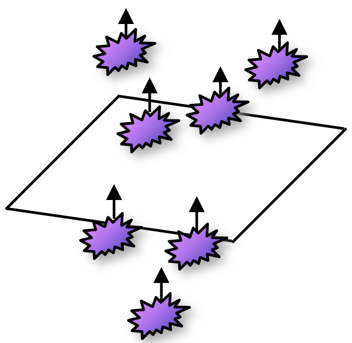
is flow rate of mass per unit (surface) area



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

Heat flux density

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



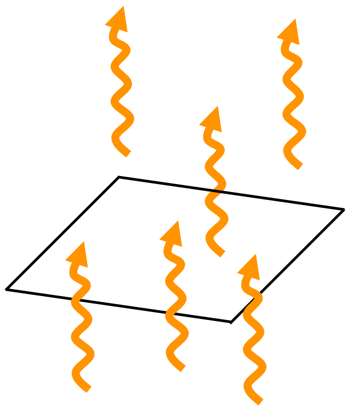
$W\ m^{-2}$

=

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

Radiant flux density

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



$W\ m^{-2}$

=

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

Take home points

- 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.
- 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.