Overview: introduction to eddy flux

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Niwot Ridge Flux Course

What is a flux?

- Transport of stuff (scalar) expressed with respect to unit area and unit time
- Has a direction and sign

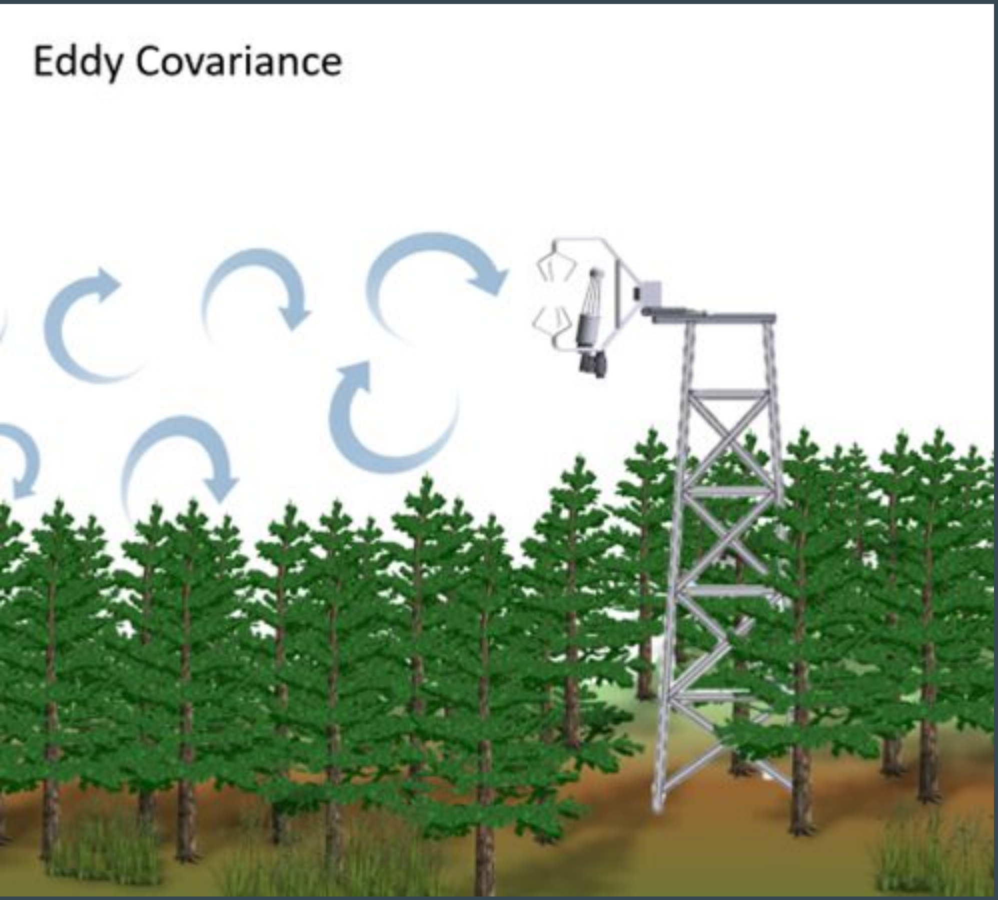
- Focus on surface flux (exchange between surface and atmosphere above it)
  - Carbon dioxide, Methane, VOC's, ozone, etc.....
  - Heat, Moisture, Momentum

- Carbon dioxide flux = "CO_2 flux" or Net Ecosystem Exchange (NEE)
  - μmol m^{-2} s^{-1} or g C m^{-2} day^{-1}
  - Positive (C added to atmosphere) or negative (C removed from atmosphere, added to ecosystem)

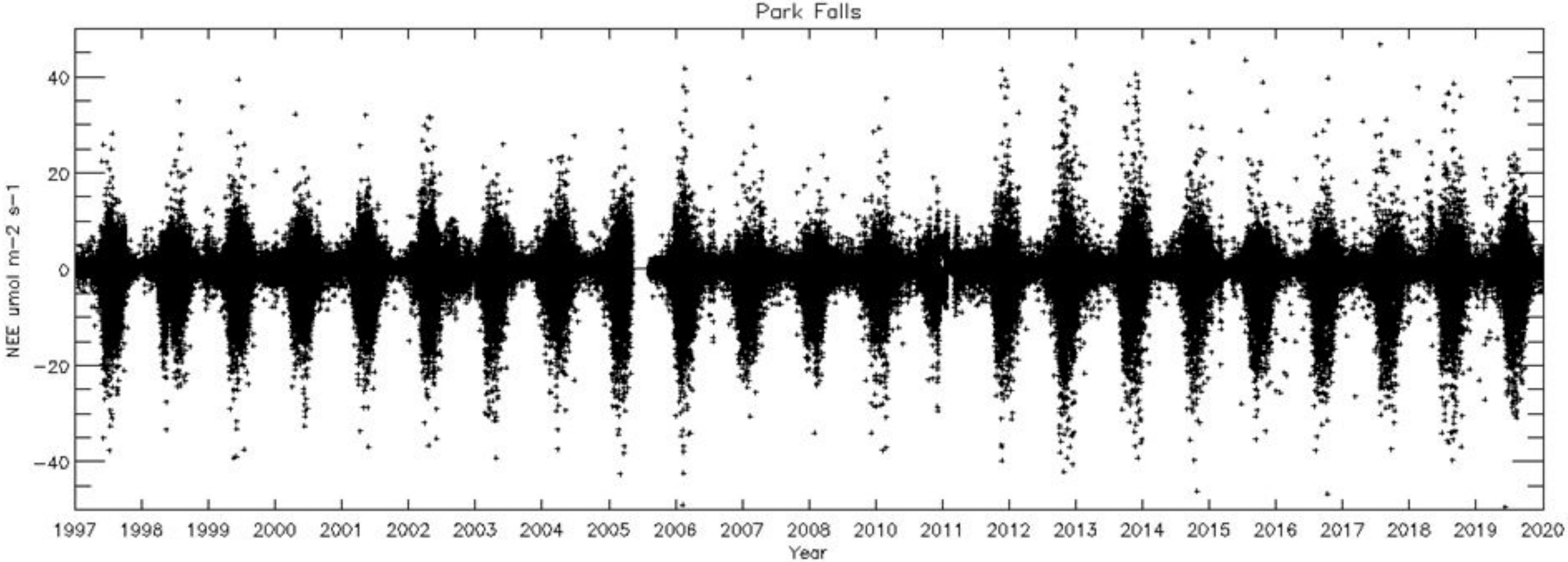
- Heat (Sensible Heat Flux)
  - Watts m^{-2} (Watt = J/s)
  - Positive (Heat added to the atmosphere)

- Moisture (Latent Heat Flux = Evapotranspiration)
  - Watts m^{-2} (Watt = J/s)
  - mm day-1
  - Positive (moisture added to the atmosphere)

Ecosystem-scale fluxes



- Site-level ecosystem process knowledge
  - Rates of carbon sequestration
  - Evapotranspiration rates
  - Rates of turbulent heat transfer to the atmosphere from the surface
  - Groundwater recharge
- Long-term trends, interannual variability


Park Falls
NEE umol m−2 s−1
40
20
0
−20
−40
1997
1998
1999
2000
2001
2002
2003
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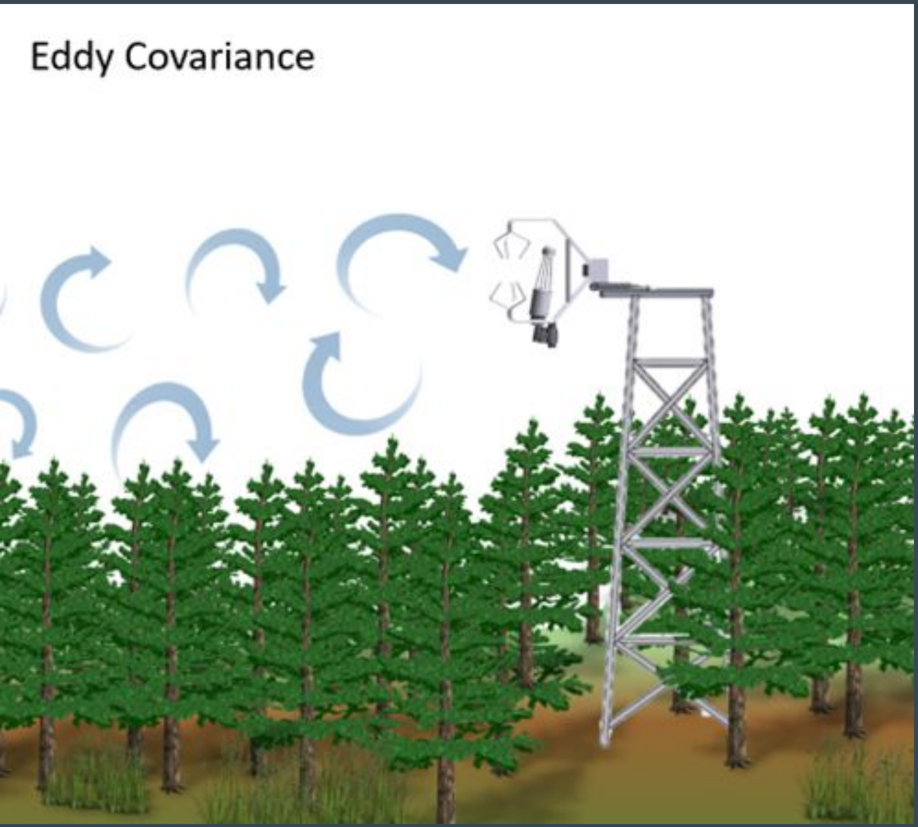
2015
2016
2017
2018
2019
2020
Year

Park Falls

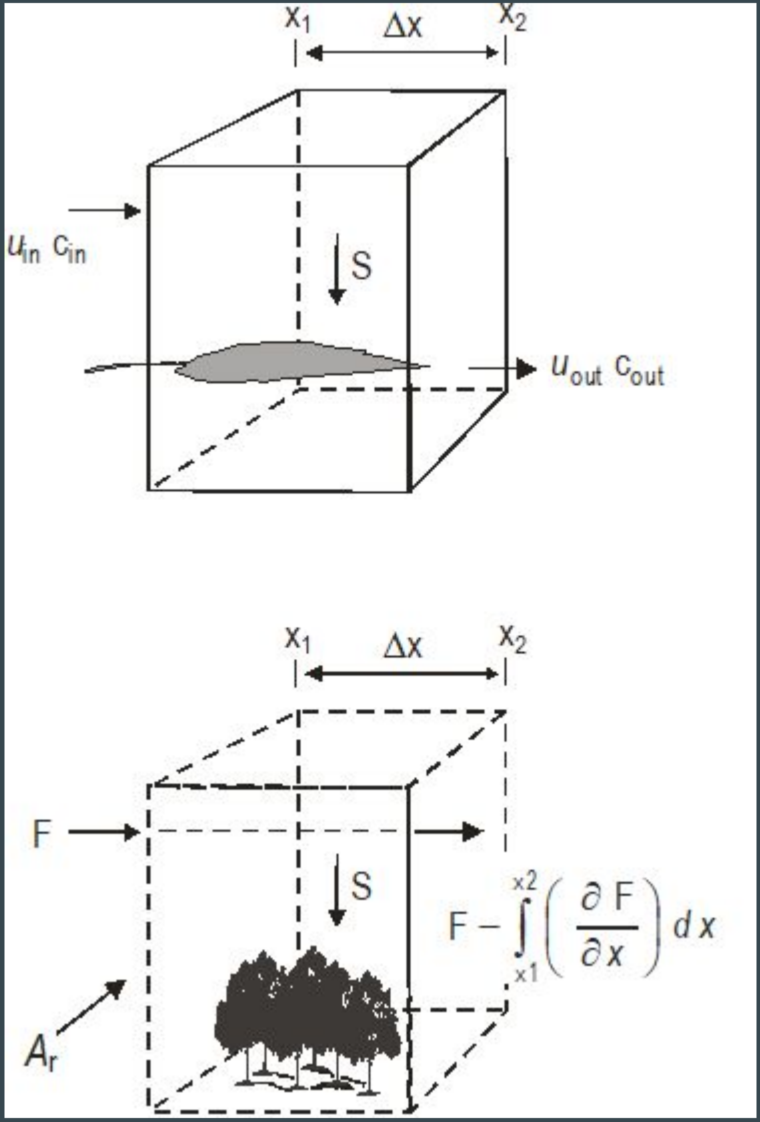
Ecosystem-scale fluxes



- Site-level ecosystem process knowledge
  - Rates of carbon sequestration
  - Evapotranspiration rates
  - Rates of turbulent heat transfer to the atmosphere from the surface
  - Groundwater recharge
- Long-term trends, interannual variability - natural climate solutions

- Time-based information for inventory needs
- Disturbance (fires, insect outbreaks, fire)
- Hot moments
- Support management decision making
- Validate global models
- Parameterize global models
- Ground-truth remote sensing products
- Test ecological principles

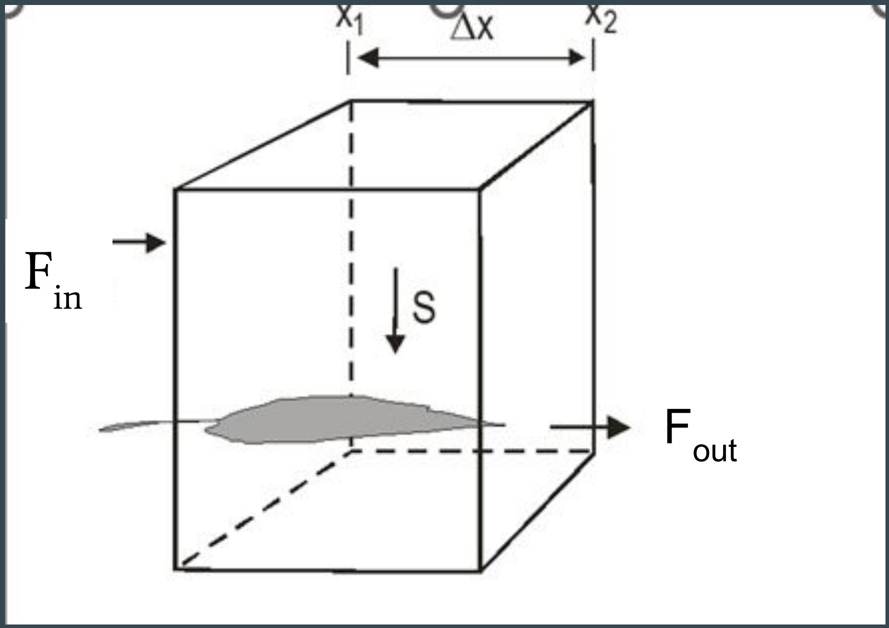
Take your pick!



Eddy flux

- Basic theory and important concepts
- Link concepts between leaf-level and ecosystem-level fluxes
- Fundamental assumptions and limitations
- Key terms
- Single towers to networks!

Flux and units with Licor chamber

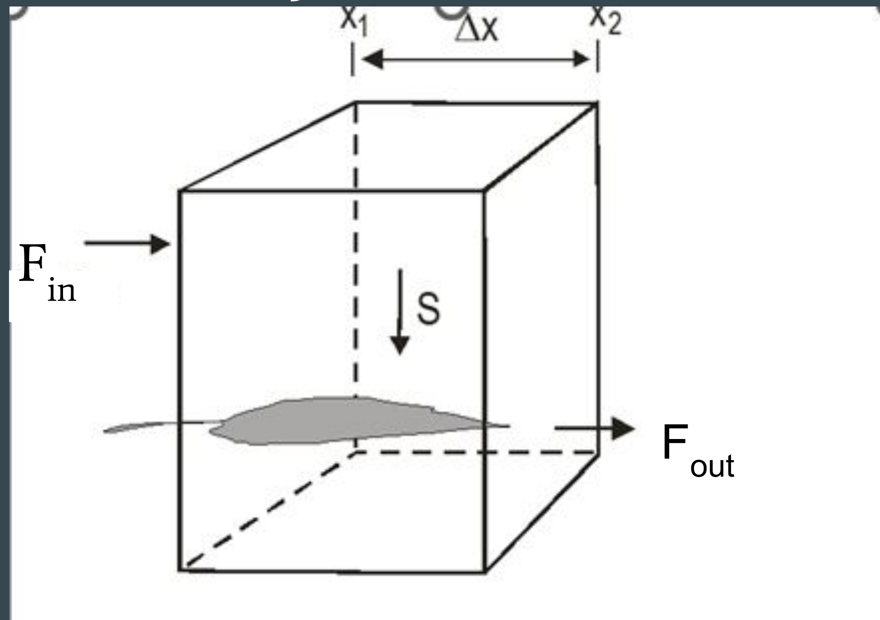


$$S = F_{in} - F_{out} = \frac{mol\ CO_2}{m^2\ s}$$

$$F_{in} = u_{in} c_{in} = \frac{mol\ (air)}{s} \times \frac{mol\ (CO_2)}{mol\ (air)} \times \frac{1}{m^2\ (leaf\ area)}$$

$$F_{out} = u_{out} c_{out} = \frac{mol\ (air)}{s} \times \frac{mol\ (CO_2)}{mol\ (air)} \times \frac{1}{m^2\ (leaf\ area)}$$

Alternatively, the flux can be expressed as an air speed (flow speed multiplied by a molar density:



$$F_{in} = u_{in} c_{in} = \frac{m}{s} \times \frac{mol\,(CO_2)}{m^3} \times \frac{1}{m^2\,(\text{leaf area})}$$

$$F_{out} = u_{out} c_{out} = \frac{m}{s} \times \frac{mol\,(CO_2)}{m^3} \times \frac{1}{m^2\,(\text{leaf area})}$$

$$S = F_{in} - F_{out} = \frac{mol\,CO_2}{m^2\,s}$$

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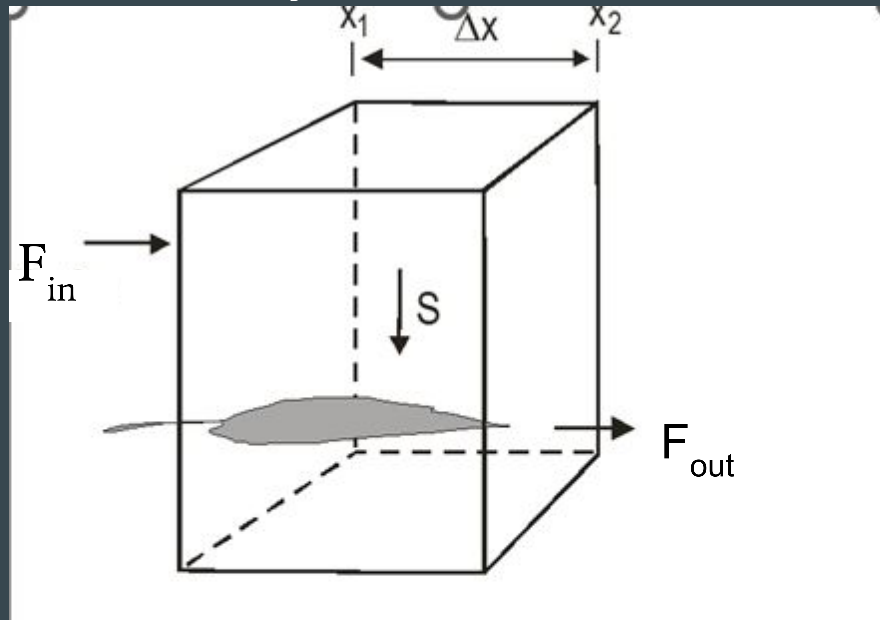
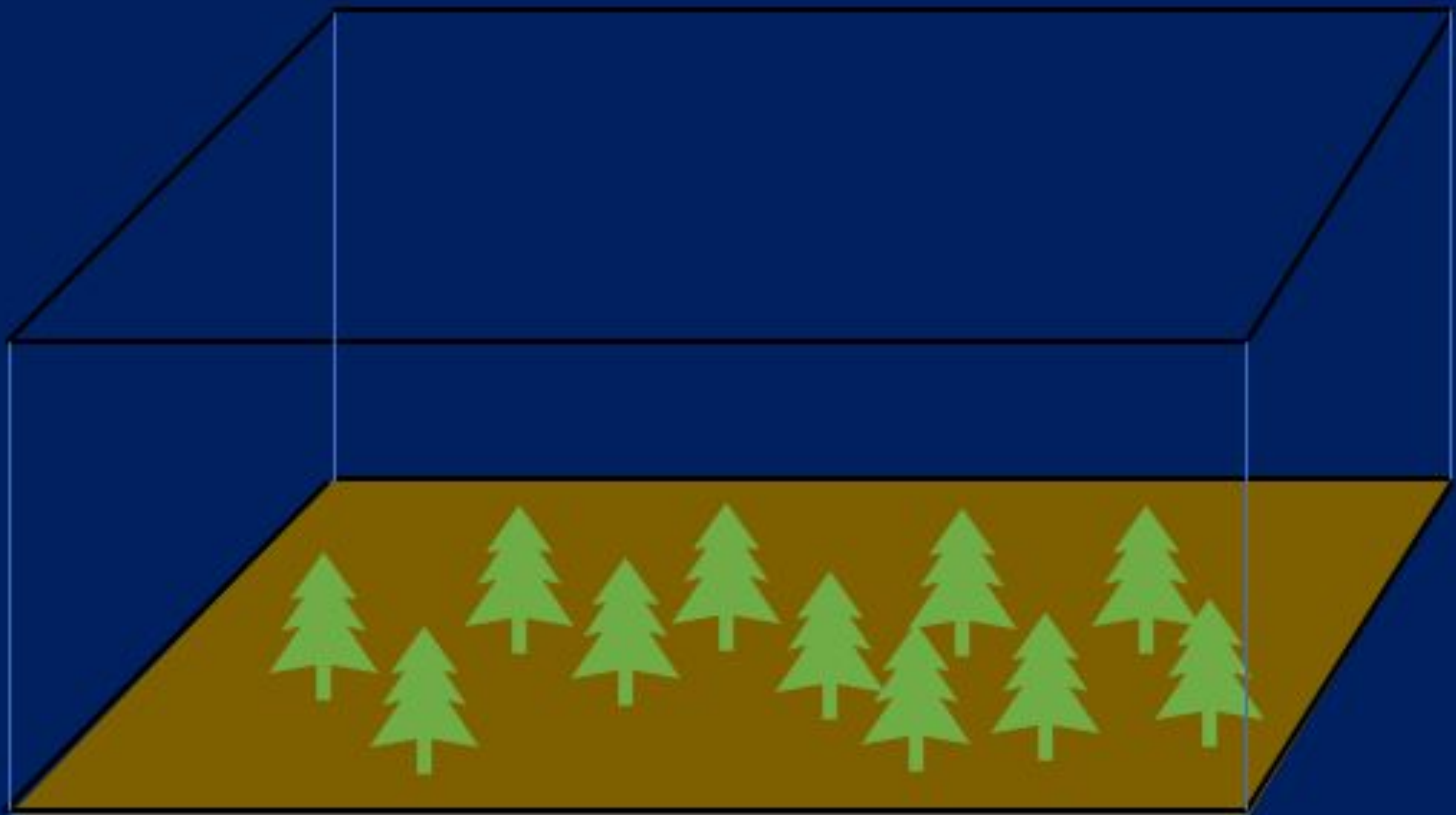


$$F_{in} = \rho_a u_{in} c_{in} = \underbrace{\frac{\text{mol (air)}}{\text{m}^3}}_{\text{density}} \times \frac{\text{m}}{\text{s}} \times \underbrace{\frac{\text{mol } (CO_2)}{\text{mol (air)}}}_{\text{Mole fraction}}$$

$$F_{out} = \rho_a u_{out} c_{out} = \underbrace{\frac{\text{mol (air)}}{\text{m}^3}}_{\text{density}} \times \frac{\text{m}}{\text{s}} \times \underbrace{\frac{\text{mol } (CO_2)}{\text{mol (air)}}}_{\text{Mole fraction}}$$

$$S = F_{in} - F_{out} = \frac{\text{mol } CO_2}{\text{m}^2 \text{ s}}$$

Now, what changes as we move up in scale to an ecosystem?



Need to consider flows in the atmosphere and turbulence

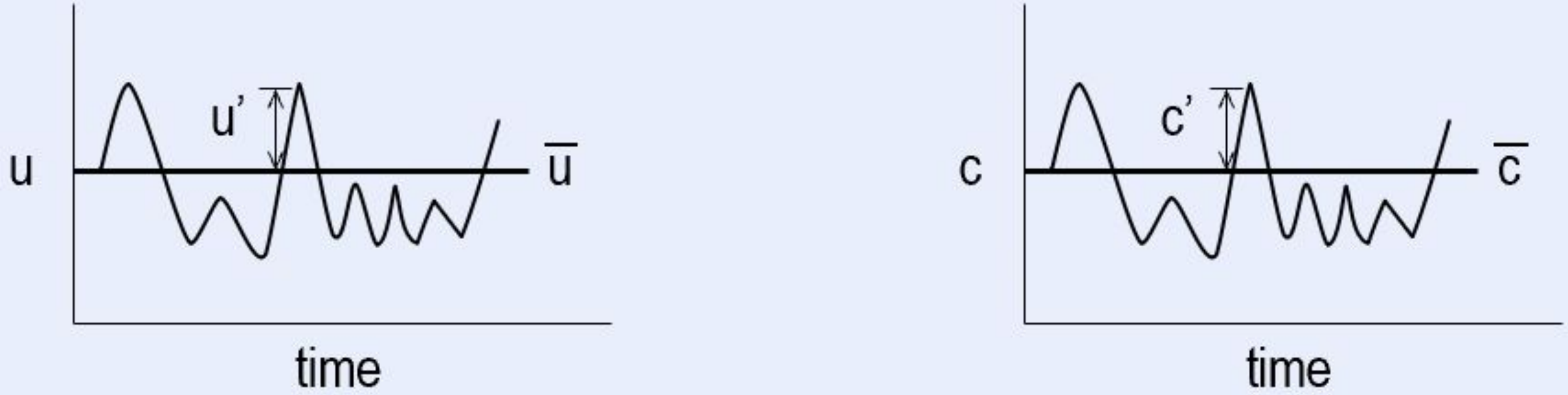
- Not consistent in either speed or direction
- Wind doesn't move past an anemometer at a constant speed - it "stutters"
- At any instant in time, the speed recorded by an anemometer reflects a **mean component and a turbulent component**

Reynold's averaging

overbar = time averaging

prime = deviation from time-averaged value

$$u = \overline{u} + u' \qquad c = \overline{c} + c'$$



Eddy flux: turbulent covariance

- Statistical covariance between turbulent component of wind (horizontal wind speed) and concentration of the scalar entity being carried by the turbulent component of the wind

Reynold's averaging

$$u = \bar{u} + u' \qquad c = \bar{c} + c'$$

we want the flux averaged over time $\overline{uc}$

$$\overline{uc} = \overline{(\bar{u} + u')(\bar{c} + c')} = \overline{\bar{u}\bar{c}} + \cancel{\overline{\bar{u}c'}} + \cancel{\overline{\bar{c}u'}} + \overline{c'u'} = \bar{u}\bar{c} + \overline{c'u'}$$

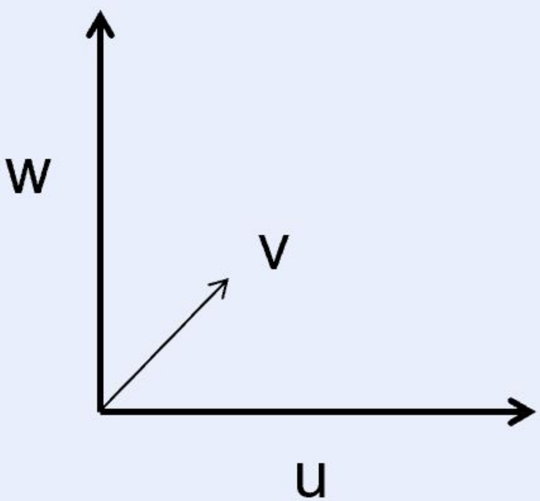
$\overline{c'} = 0$ $\overline{u'} = 0$

advection

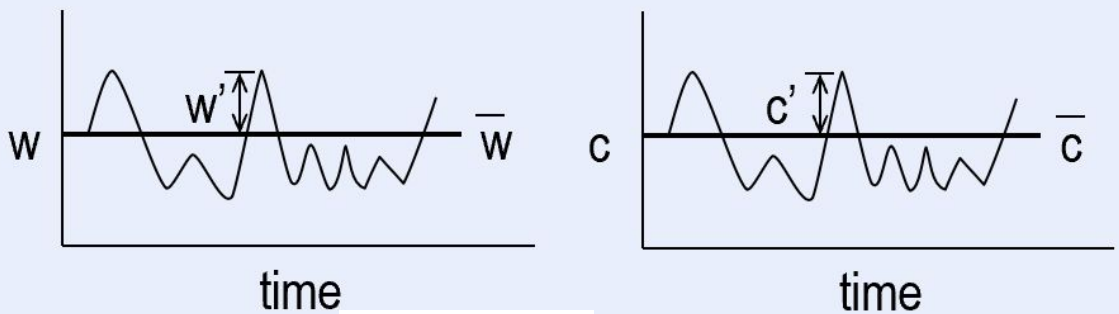
covariance

The covariance in which we are typically most interested is the vertical turbulent covariance – $\overline{w'c'}$

Reynold's averaging



$$w = \overline{w} + w' \qquad c = \overline{c} + c'$$



$$\overline{w} = 0$$

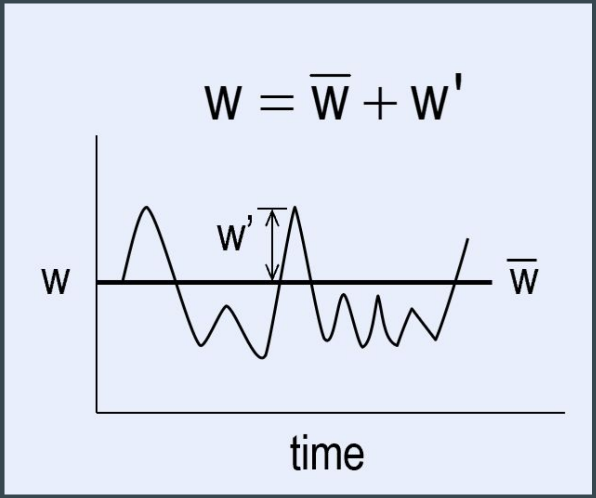
$$\overline{uc} = \overline{u}\,\overline{c} + \overline{c'u'} \qquad \overline{wc} = \overline{w}\,\overline{c} + \overline{c'w'}$$

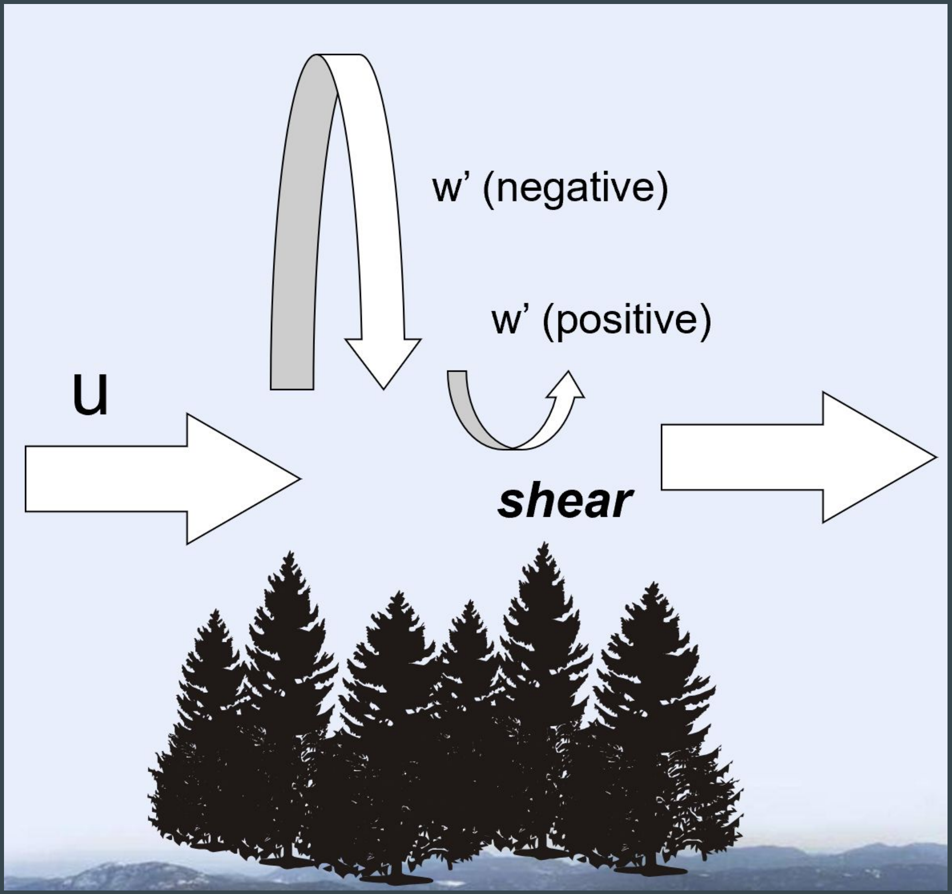
Advection

Covariance

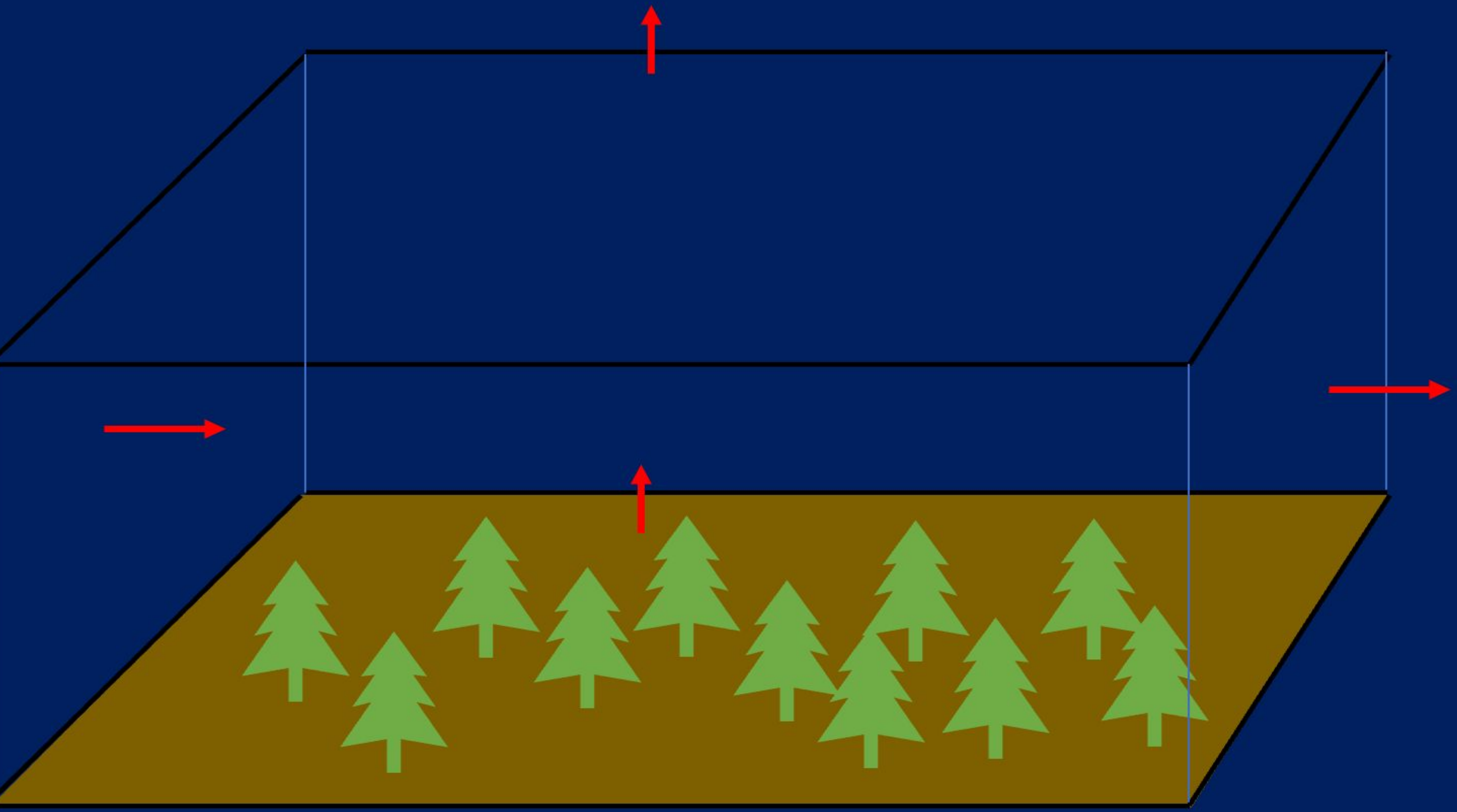
What drives the vertical turbulent flux?

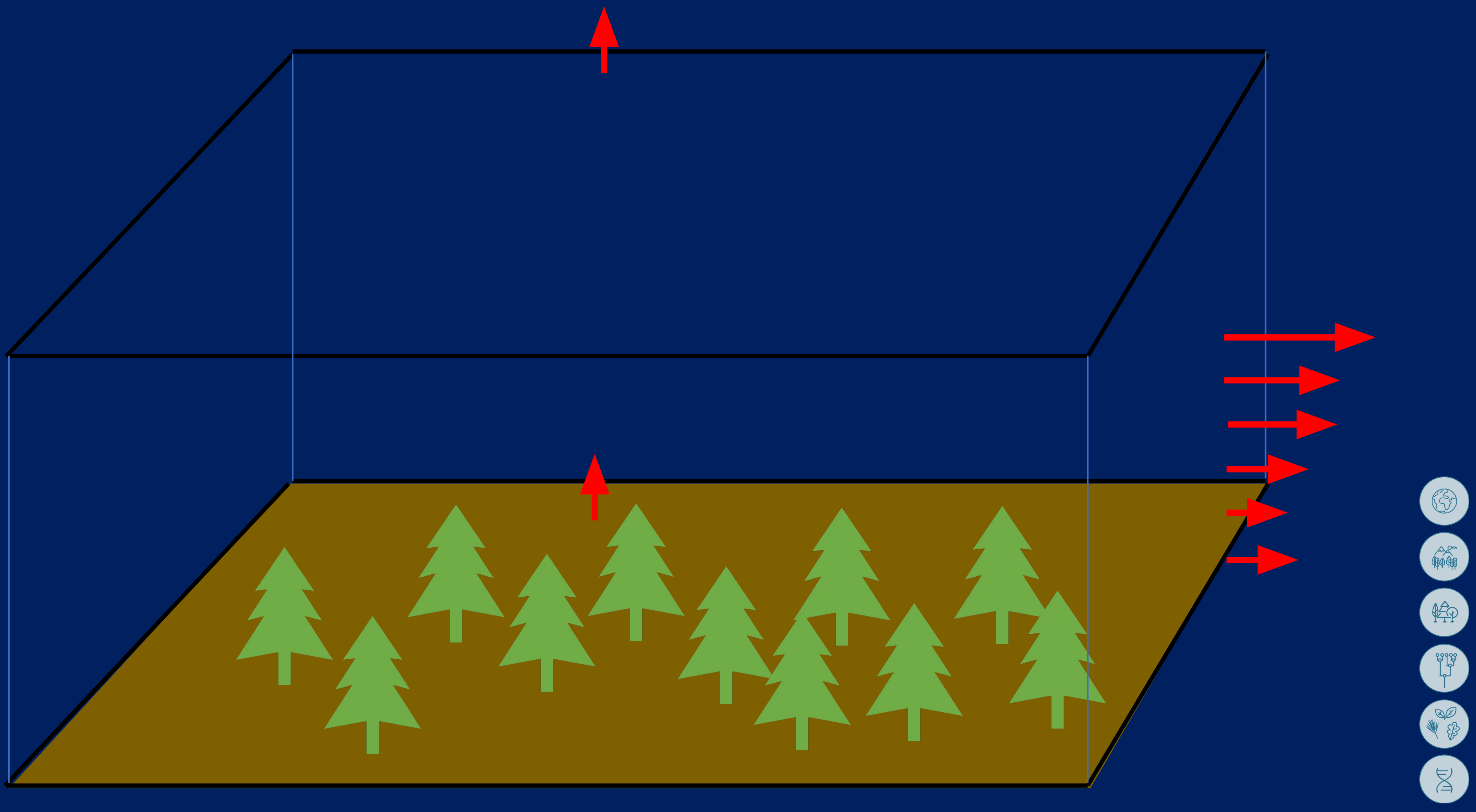
- Shear stress
- Roughness
- Friction
- Eddies





What if we open up the box?



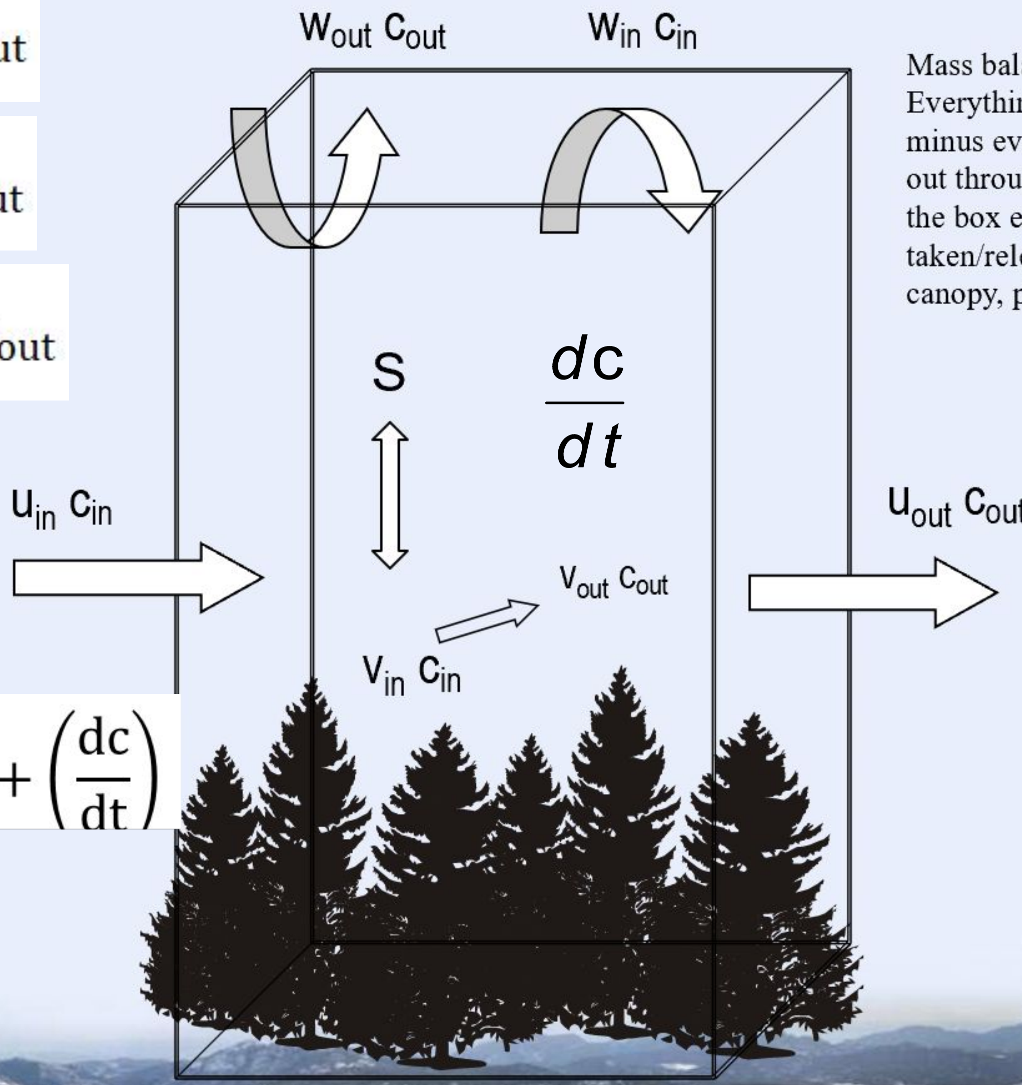


The wind works within a 3-D coordinate system, so the flux vectors are not as neatly sorted as they are with a leaf chamber

$$\Delta F_x = u_{in}c_{in} - u_{out}c_{out}$$

$$\Delta F_y = v_{in}c_{in} - v_{out}c_{out}$$

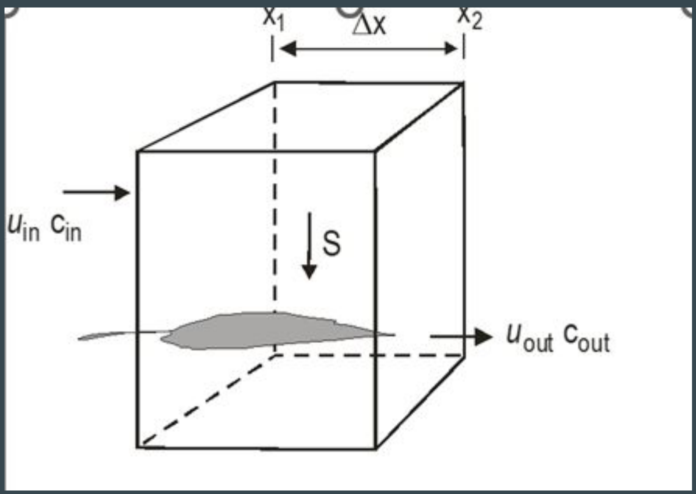
$$\Delta F_z = w_{in}c_{in} - w_{out}c_{out}$$

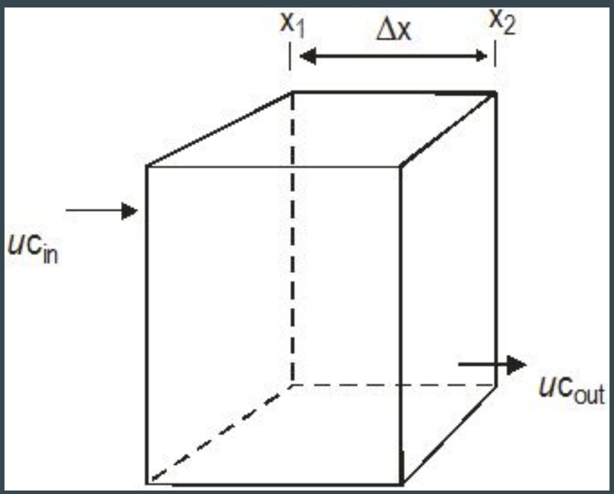


Mass balance:
Everything that goes in minus everything that goes out through the surfaces of the box equals what is taken/released by the canopy, plus storage

$$\frac{\Delta F_x}{\Delta x} + \frac{\Delta F_y}{\Delta y} + \frac{\Delta F_z}{\Delta z} = S + \left(\frac{dc}{dt}\right)$$

Mass Balance key to remember here





$$S = u_{in} c_{in} - u_{out} c_{out}$$

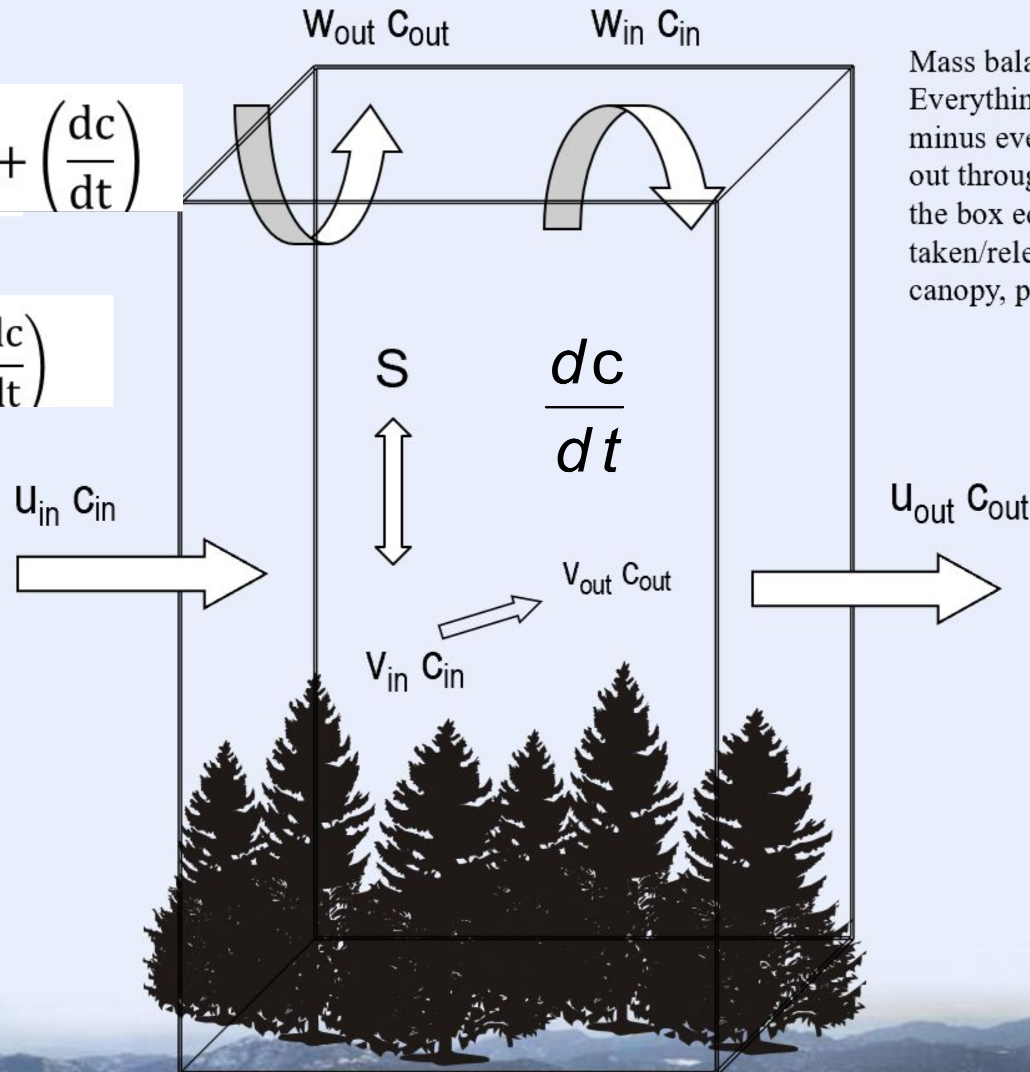
$$S = u_{in} c_{in} - u_{out} c_{out}$$

Change in concentration of quantity in the fixed volume, must be matched by source/sink activity

In an empty chamber (no sources or sinks) $F_{in} = F_{out}$ and $\Delta c/\Delta t = 0$.

$$\frac{\Delta F_x}{\Delta x} + \frac{\Delta F_y}{\Delta y} + \frac{\Delta F_z}{\Delta z} = S + \left(\frac{dc}{dt}\right)$$

$$\cancel{\frac{\partial F_x}{\partial x}} + \cancel{\frac{\partial F_y}{\partial y}} + \frac{\partial F_z}{\partial z} = S + \left(\frac{dc}{dt}\right)$$

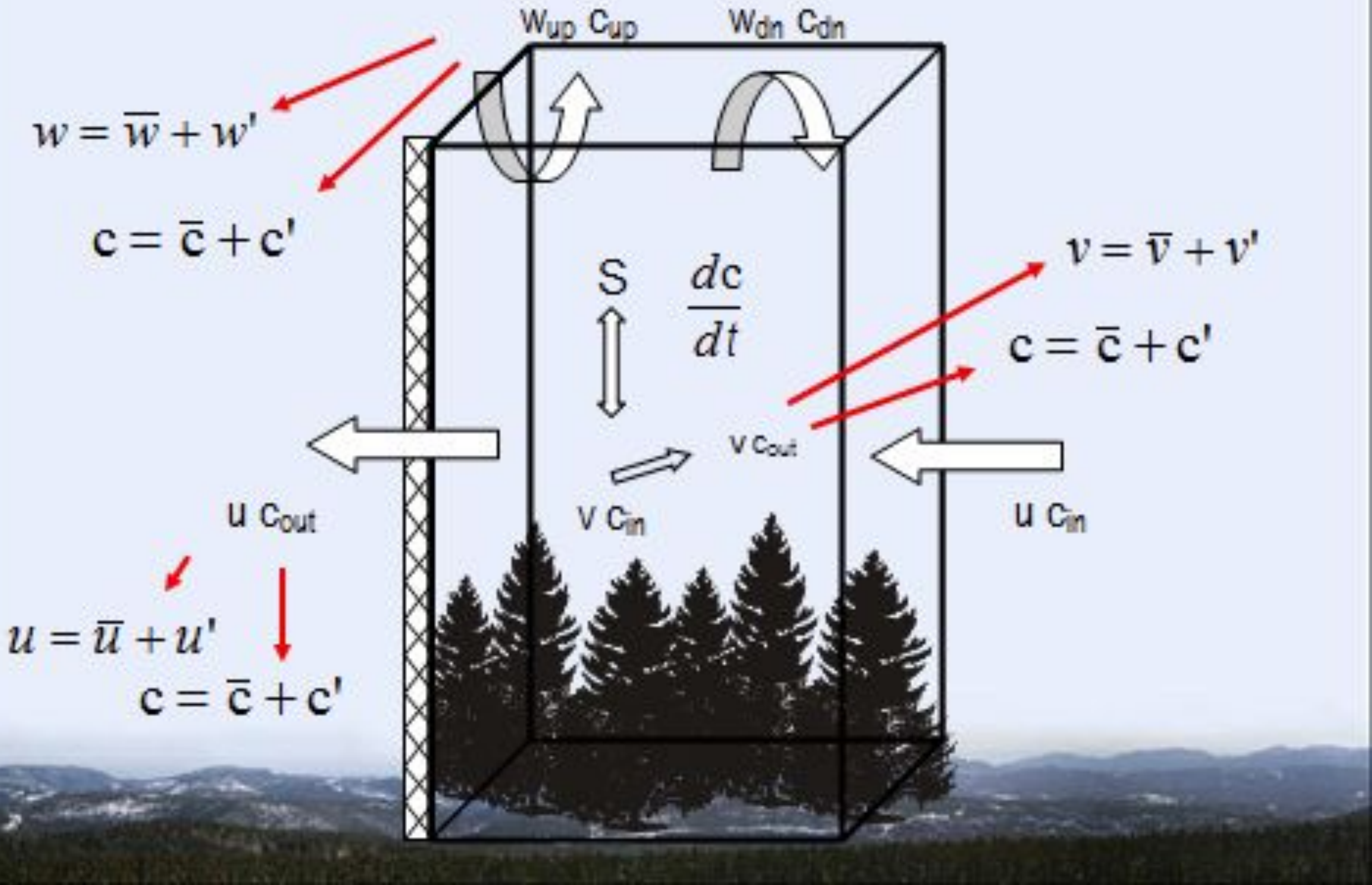


Mass balance:
Everything that goes in minus everything that goes out through the surfaces of the box equals what is taken/released by the canopy, plus storage

If we assume horizontal homogeneity, horizontal gradients nullify

$$\frac{\partial}{\partial x} = 0 \qquad \frac{\partial}{\partial y} = 0$$

Applying Reynolds averaging to our wind flows through our hypothetical control volume

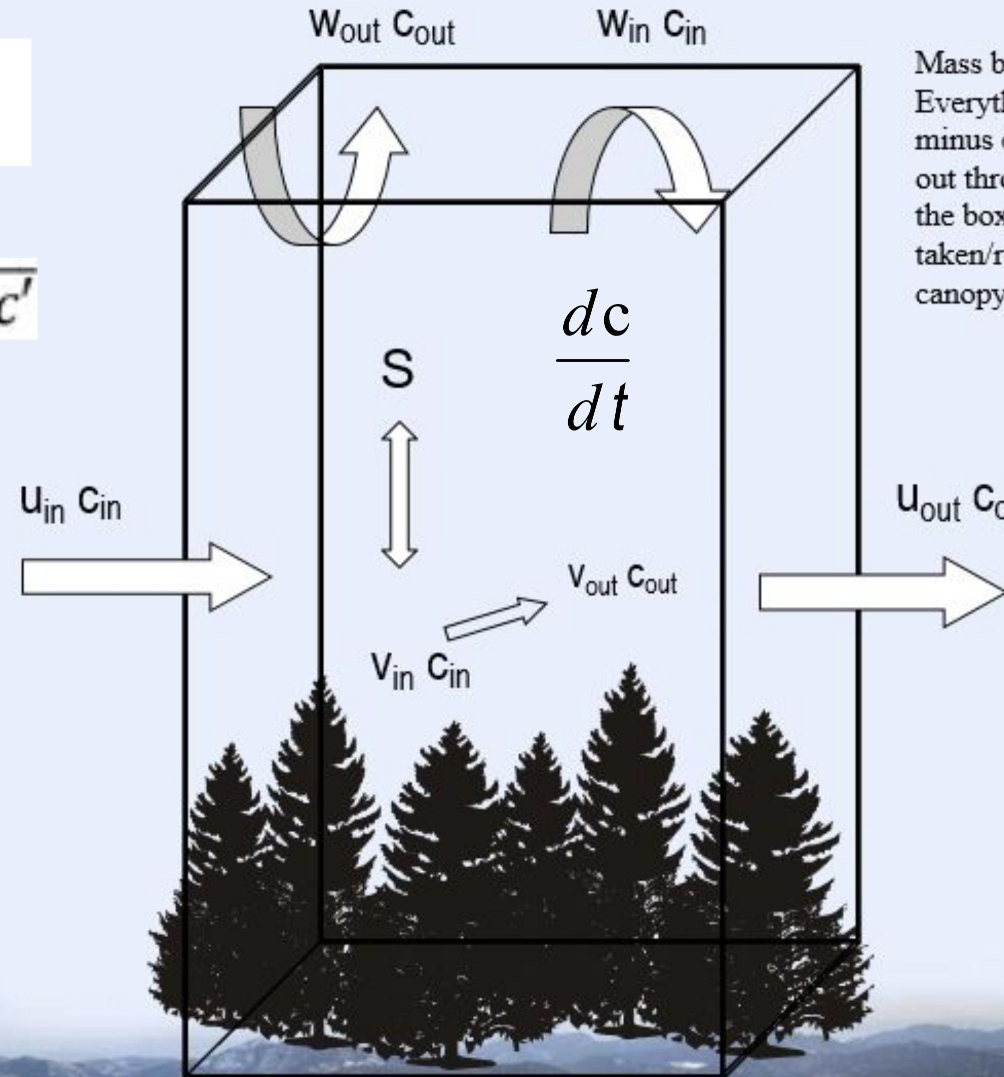


$$\frac{\partial F_z}{\partial z} = S + \left(\frac{dc}{dt}\right)$$

$$F_z = \overline{wc} = \bar{w}\bar{c} + \overline{w'c'}$$

$$\bar{w} = 0$$

$$\frac{\partial(\overline{w'c'})}{\partial z} = S + \left(\frac{dc}{dt}\right)$$



Mass balance:
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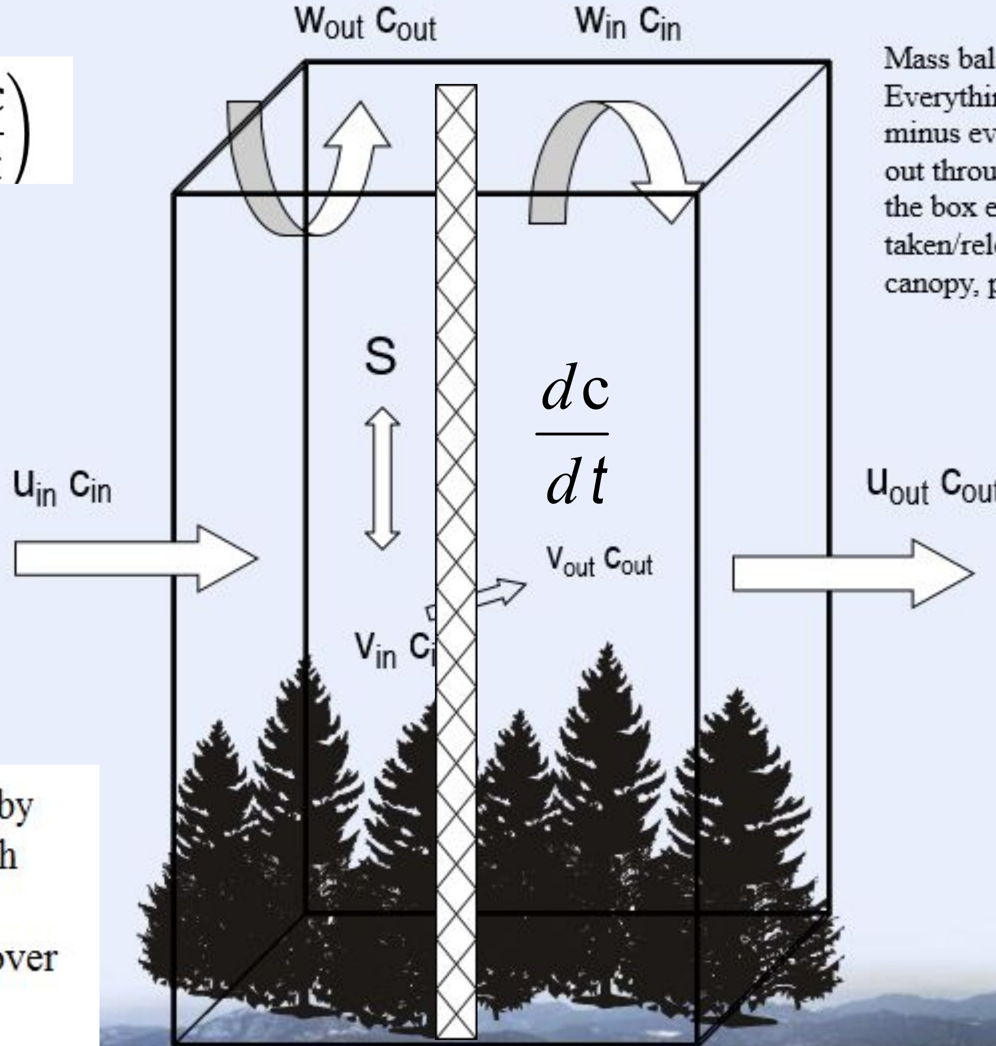
$$\frac{\partial(\overline{w'c'})}{\partial z} = S + \left(\frac{dc}{dt}\right)$$



Mass balance:
Everything that goes in minus everything that goes out through the surfaces of the box equals what is taken/released by the canopy, plus storage

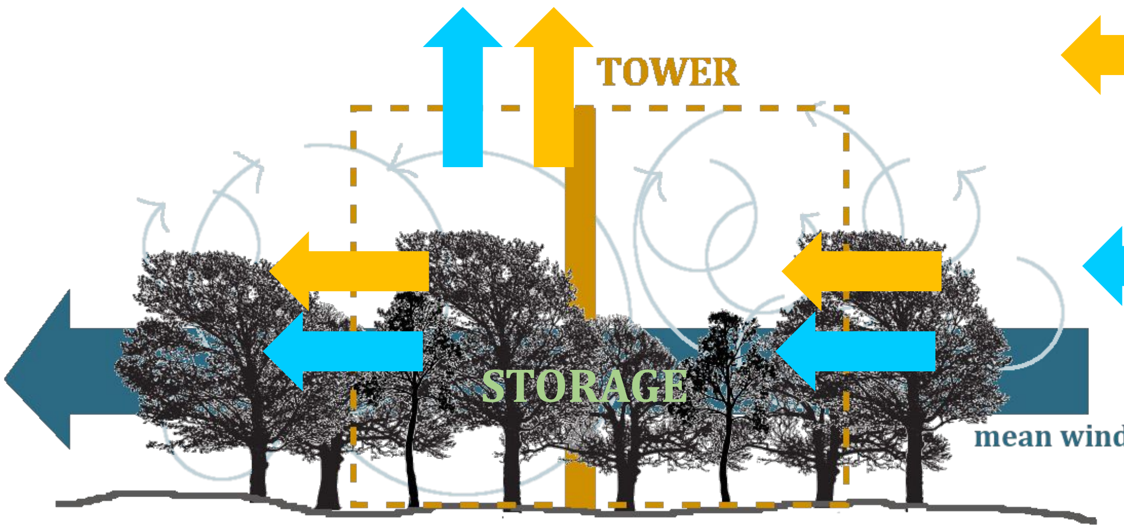
$$\int_0^h \frac{\partial(\overline{w'c'})}{\partial z} dz = \int_0^h S dz = F_c$$

Assumption: A flux measured by an eddy covariance system high enough above the canopy represents the integrated flux over all heights

$$\int S(z)dz = \int \frac{\partial C}{dt} dz + \overline{w'c'}$$

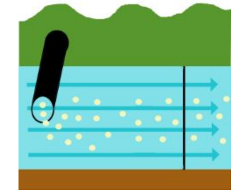
And…..of course cannot ignore storage

Fundamental Assumptions and limitations



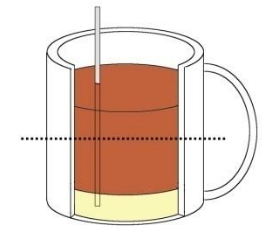
Advective flux

$\vec{U} \cdot C$



Turbulent flux

$\overline{U'C'}$



$$\mathrm{NEE} = \cancel{\int_0^z \frac{\partial \bar{u}\bar{c}}{\partial x} dz} + \cancel{\int_0^z \frac{\partial \bar{v}\bar{c}}{\partial y} dz} + \cancel{\int_0^z \frac{\partial \bar{w}\bar{c}}{\partial z} dz} + \cancel{\int_0^z \frac{\partial \overline{u'c'}}{\partial x} dz} + \cancel{\int_0^z \frac{\partial \overline{v'c'}}{\partial y} dz} + \int_0^z \frac{\partial \overline{w'c'}}{\partial z} dz + \int_0^z \frac{\partial \bar{c}}{\partial t} dz$$

Advective fluxes in 3 directions **Turbulent fluxes in 3 directions** **Storage**