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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)

- $\mu$mol 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
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!

From: Burba, G. et al., 2019. DOI: 10.13140/RG.2.2.25992.67844
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

\[ S = F_{\text{in}} - F_{\text{out}} = \frac{\text{mol CO}_2}{\text{m}^2 \text{ s}} \]

\[ F_{\text{in}} = u_{\text{in}} c_{\text{in}} = \frac{\text{mol (air)}}{\text{s}} \times \frac{\text{mol (CO}_2)}{\text{mol (air)}} \times \frac{1}{\text{m}^2 \text{ (leaf area)}} \]

\[ F_{\text{out}} = u_{\text{out}} c_{\text{out}} = \frac{\text{mol (air)}}{\text{s}} \times \frac{\text{mol (CO}_2)}{\text{mol (air)}} \times \frac{1}{\text{m}^2 \text{ (leaf area)}} \]
Alternatively, the flux can be expressed as an air speed (flow speed multiplied by a molar density):

\[
\begin{align*}
F_{\text{in}} &= u_{\text{in}} c_{\text{in}} = \frac{m}{s} \times \frac{\text{mol (CO}_2\text{)}}{m^3} \times \frac{1}{m^2 \text{ (leaf area)}} \\
F_{\text{out}} &= u_{\text{out}} c_{\text{out}} = \frac{m}{s} \times \frac{\text{mol (CO}_2\text{)}}{m^3} \times \frac{1}{m^2 \text{ (leaf area)}} \\
S &= F_{\text{in}} - F_{\text{out}} = \frac{\text{mol CO}_2}{m^2 \text{ s}}
\end{align*}
\]
Alternatively, the flux can be expressed as an air speed (flow speed multiplied by a molar density):

\[
F_{in} = \rho_a u_{in} c_{in} = \frac{\text{mol (air)}}{m^3} \times \frac{m}{s} \times \frac{\text{mol (CO}_2)}{\text{mol (air)}},
\]

\[
F_{out} = \rho_a u_{out} c_{out} = \frac{\text{mol (air)}}{m^3} \times \frac{m}{s} \times \frac{\text{mol (CO}_2)}{\text{mol (air)}},
\]

\[
S = F_{in} - F_{out} = \frac{\text{mol CO}_2}{m^2 s}.
\]
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

\[ u = \bar{u} + u' \quad c = \bar{c} + c' \]

\(\overline{\text{overbar}}\) = time averaging

\(\prime\) = deviation from time-averaged value
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

\[ u = \bar{u} + u' \quad c = \bar{c} + c' \]

\[ u \quad \bar{u} \quad u' \quad c \quad \bar{c} \]

We want the flux averaged over time \( \bar{uc} \)

\[ \bar{uc} = (\bar{u} + u')(\bar{c} + c') = \bar{uc} + \bar{uc}' + \bar{uc}' + \bar{uc} = \bar{uc} + c'u' \]

\[ \bar{c}' = 0 \quad \bar{u}' = 0 \]

Advection

Covariance
The covariance in which we are typically most interested is the vertical turbulent covariance \( \overline{w'c'} \).

Reynold’s averaging

\[
\bar{w} = \overline{w} + w' \\
\bar{c} = \overline{c} + c'
\]

\[
\overline{uc} = \overline{uc} + c'u' \\
\overline{wc} = \overline{wc} + c'w'
\]

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.
Mass Balance key to remember here

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

\[ S = u_{in} c_{in} - u_{out} c_{out} \]

In an empty chamber (no sources or sinks) \( F_{in} = F_{out} \) and \( \Delta c/\Delta t = 0 \).
If we assume horizontal homogeneity, horizontal gradients nullify

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

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

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

\[
\partial \frac{\partial}{\partial x} = 0 \quad \partial \frac{\partial}{\partial y} = 0
\]
Applying Reynolds averaging to our wind flows through our hypothetical control volume

\[ w = \bar{w} + w' \]

\[ c = \bar{c} + c' \]

\[ u = \bar{u} + u' \]

\[ v = \bar{v} + v' \]

\[ \frac{dc}{dt} = S + v c_{\text{out}} - u c_{\text{in}} \]
\[ \frac{\partial F_z}{\partial z} = S + \left( \frac{dc}{dt} \right) \]

\[ F_z = \overline{wc} = \overline{wc} + \overline{w}c' \]

\[ \overline{w} = 0 \]

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

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.
\[
\frac{\partial (w'c')}{\partial z} = S + \left( \frac{dc}{dt} \right)
\]

\[
\int_0^h \frac{\partial (w'c')}{\partial z} \, dz = \int_0^h S \, dz = F_c
\]

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

And.....of course cannot ignore storage.
Fundamental Assumptions and limitations

Advective flux: $\vec{U} \cdot \vec{C}$

Turbulent flux: $\overline{U'C'}$

Storage

\[
\text{NEE} = \int_0^z \frac{\partial \overline{u'C'}}{\partial x} \, dz + \int_0^z \frac{\partial \overline{v'C'}}{\partial y} \, dz + \int_0^z \frac{\partial \overline{w'C'}}{\partial z} \, dz + \int_0^z \frac{\partial \overline{u'c'}}{\partial x} \, dz + \int_0^z \frac{\partial \overline{v'c'}}{\partial y} \, dz + \int_0^z \frac{\partial \overline{w'c'}}{\partial z} \, dz + \int_0^z \frac{\partial \overline{c}}{\partial t} \, dz
\]

Advective fluxes in 3 directions  Turbulent fluxes in 3 directions  Storage