China Flux 2021

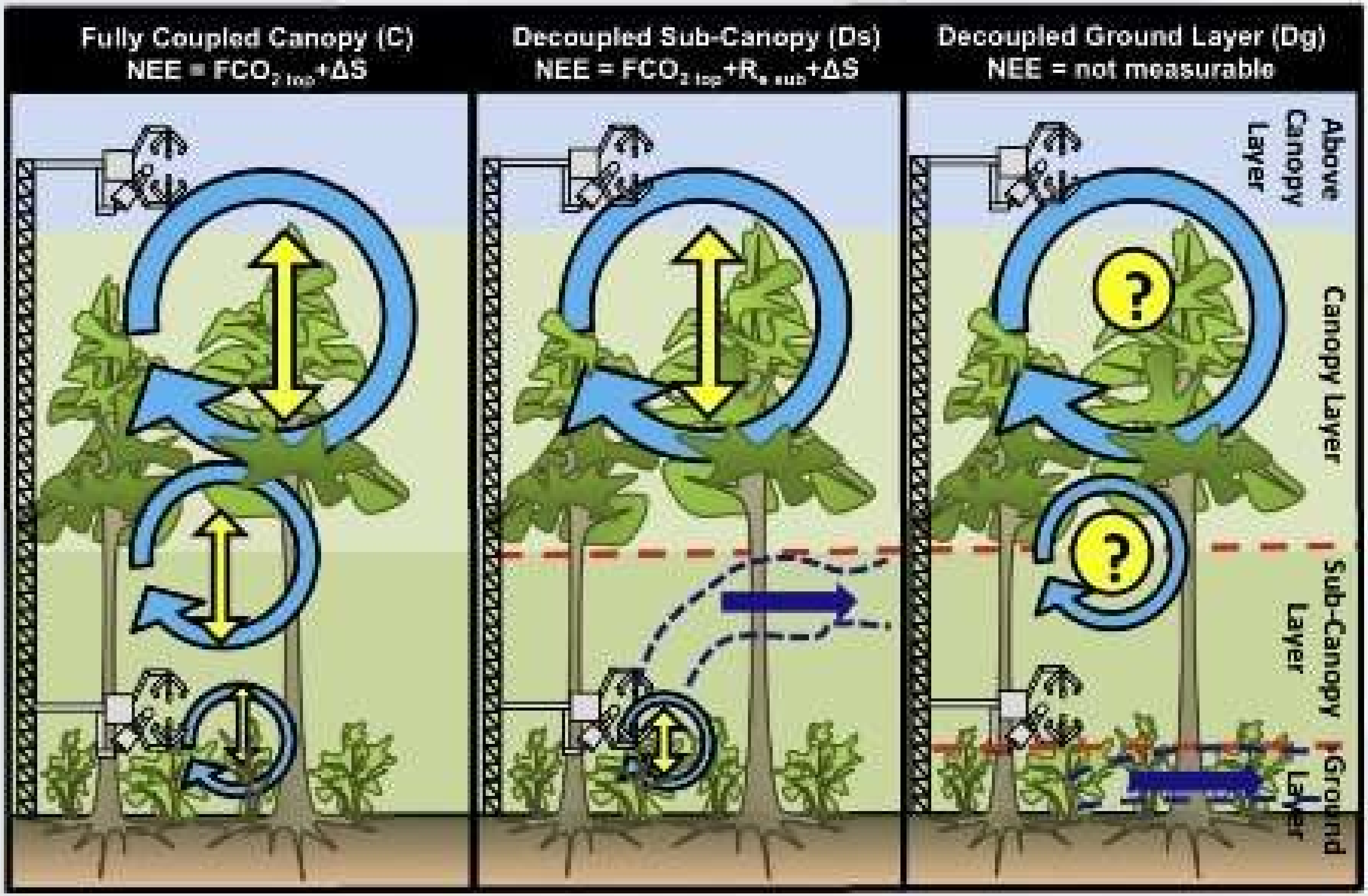
Net Ecosystem Exchange Equation of CO_2/H_2O and other Trace Gas

General Outline

- NEE
- Eddy Covariance and Conservation Equation
- Storage
- Advection

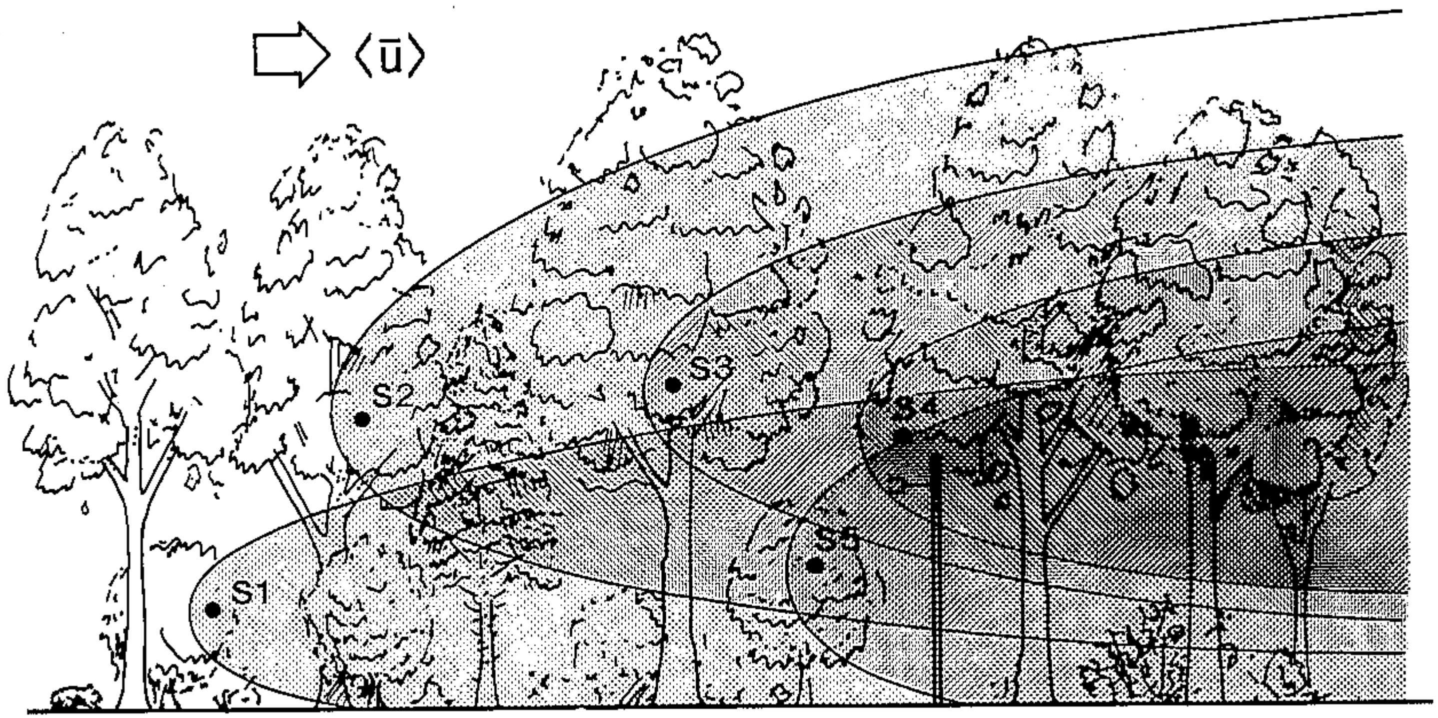

CAMPBELL SCIENTIFIC
EC150

The approach



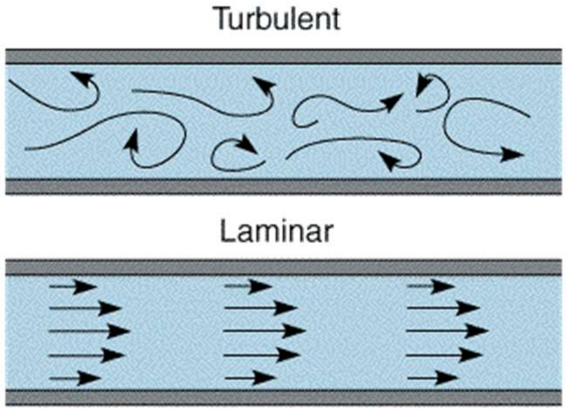
Thomas et al., 2013; Jocher et al., 2018

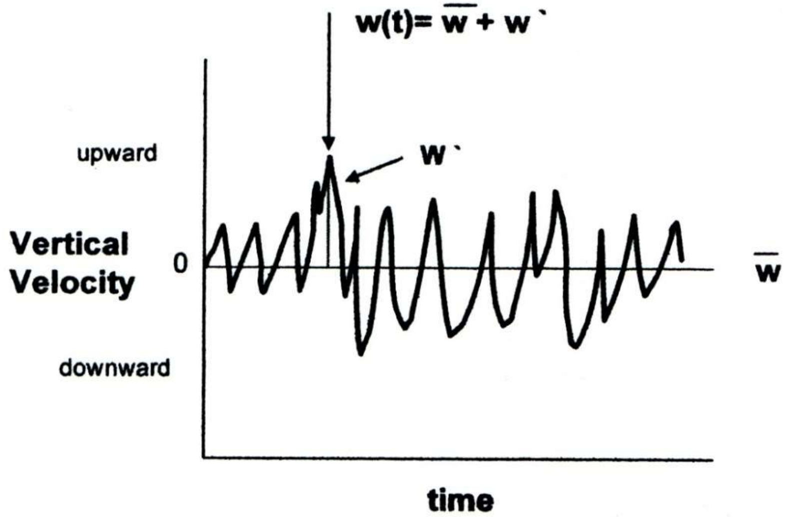
The sources and sinks in the forest are complex to the flux



NEE: Net Ecosystem Exchange: The balance of CO_2 per unit area between plants and animals, including soil and microorganisms and their environment (positive away from surface negative towards the surface)

Viscous Flow has a mean component and a turbulent component: **Reynolds Averaging**



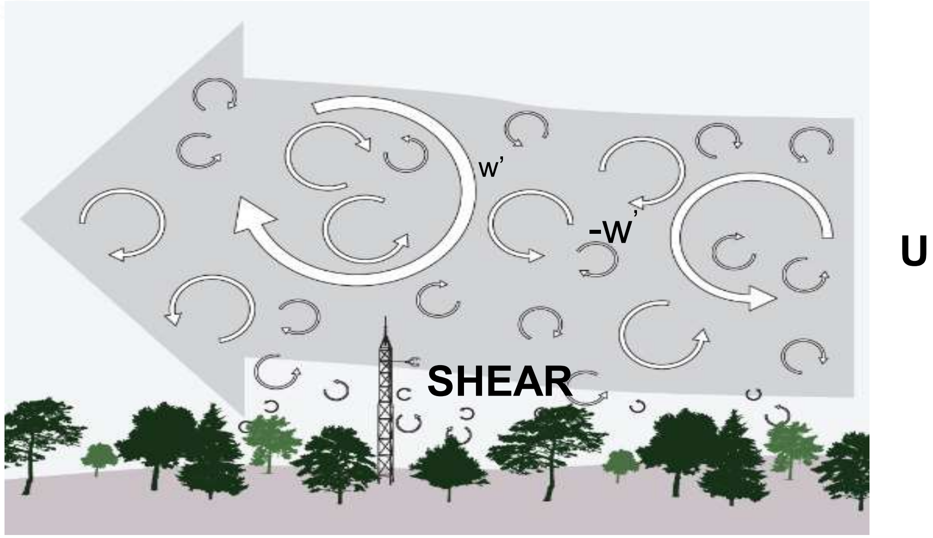


$w(t) = \overline{w} + \acute{w}$ $\quad$ $c(t) = \overline{c} + \acute{c}$

Turbulent covariance is eddy flux density!

u= wind speed blowing parallel to mean
v= wind speed blowing perpendicular to mean
w= vertical wind speed
c= scalar

Turbulent Transport



Turbulence is quasi-chaotic motion of swirling parcels of air called eddies. Caused by surface forcings (solar heating, wind shears from frictional drag, and turbulent wakes from obstacles and uneven terrain).

If surface forcings are insufficient, flow will be laminar.

Turbulence is orders of magnitude more efficient at mixing than diffusion. (Stull, 1988)

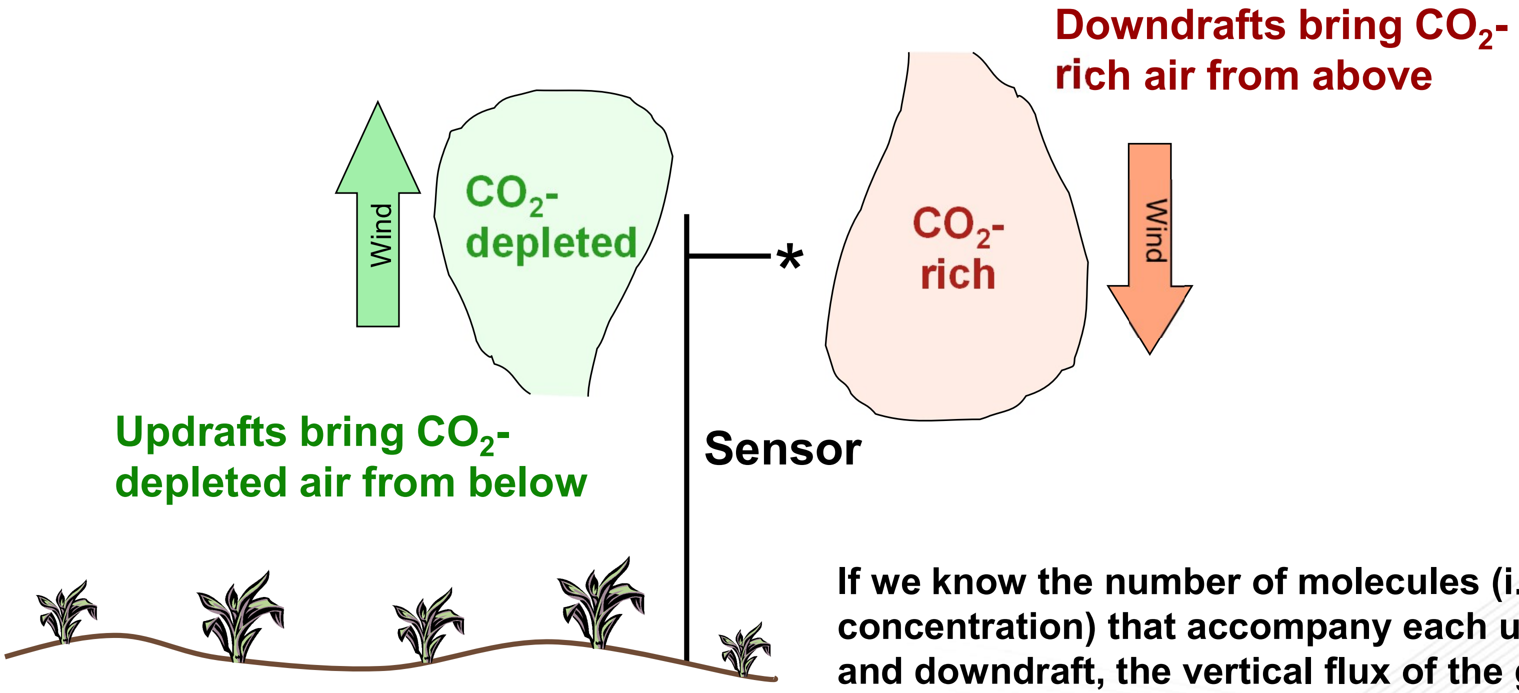
http://fdrc.iit.edu/research/images/

Eddy Covariance

Under unstable conditions, most of the flux is transported by turbulence and can be measured using eddy covariance (EC).

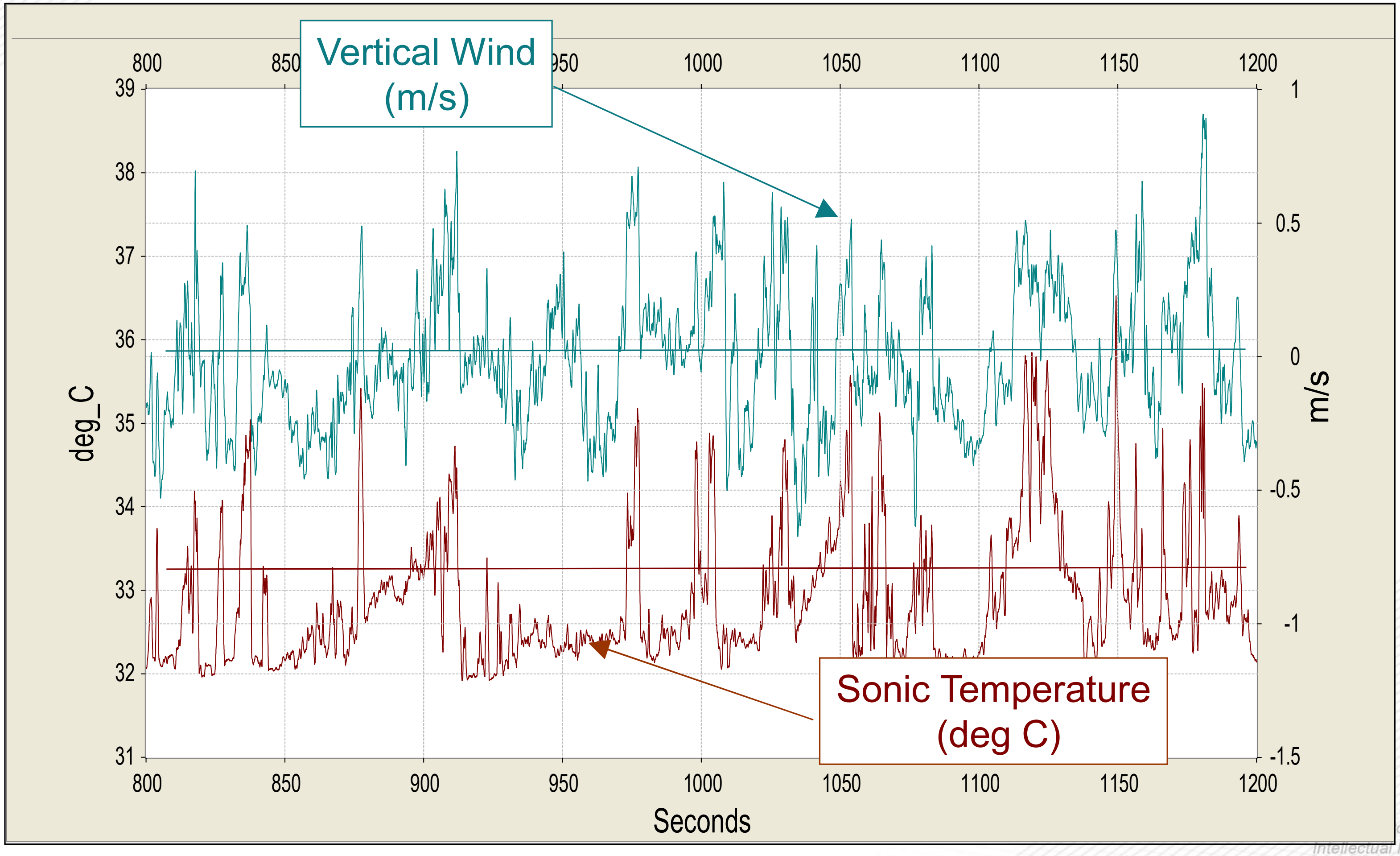
Correlation exists between vertical motions and atmospheric properties

Example: CO_2 Flux at a Photosynthetically-Active Surface Boundary Layer

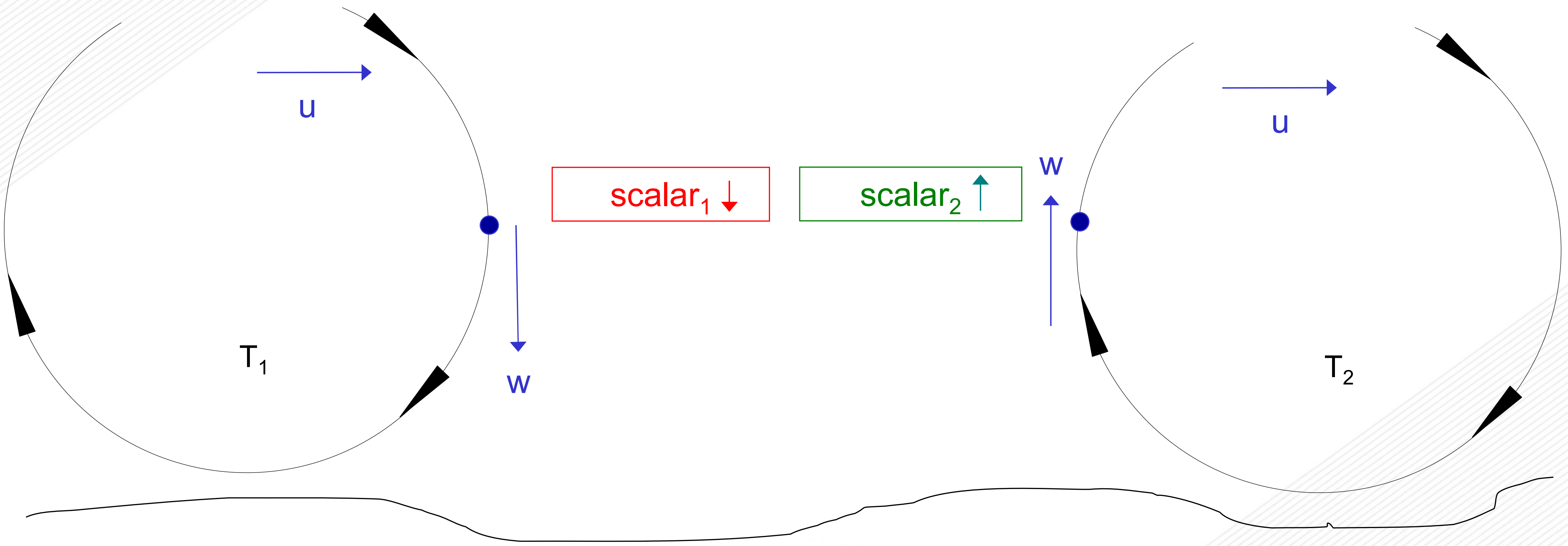


If we know the number of molecules (i.e., concentration) that accompany each updraft and downdraft, the vertical flux of the gas can be calculated at that point over a certain time interval.

Eddy Covariance Time Series: W and Ts



Eddy Covariance General Principals



Turbulence (cont'd)

$$w(t) = \overline{w} + w'$$ **Vertical wind**

$$c(t) = \overline{c} + c'$$ **CO2 Density**

Reynolds Averaging Rules

1. $\overline{A'} = 0$
2. $\overline{(A+B)} = \overline{A} + \overline{B}$
3. $\overline{\overline{A}B} = \overline{A}\overline{B}$

$$F_c(t) = \overline{w(t)c(t)} = \overline{\left(\overline{w} + w'\right)\left(\overline{c} + c'\right)}$$

Reynolds Averaging Rules

$\overline{w}$ tends to 0 over time

$$F_c = \overline{w}\,\overline{c} + \overline{w'c'}$$

$$F_c = \overline{w'c'}$$

What about horizontal turbulent fluxes???

We purposely select a site where we assume a horizontally homogeneous equilibrium layer, which implies (Finnigan, 2003):

1. Horizontal concentration gradients are negligible

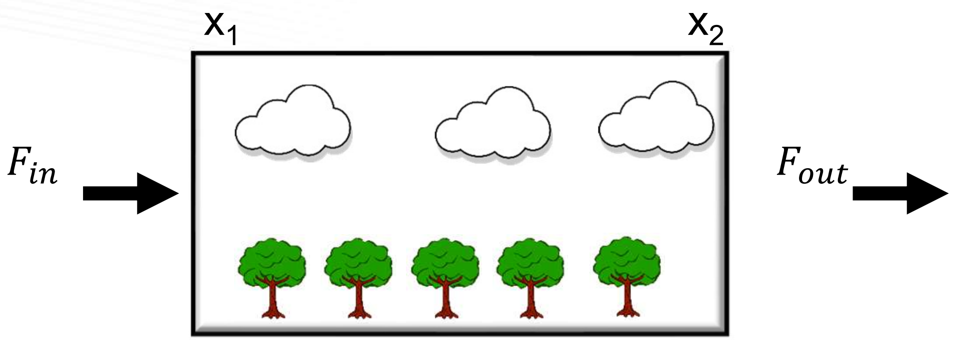
2. Net horizontal flux is zero

3. Measured vertical turbulent flux is representative of the total turbulent flux of the footprint area

Continuity: Conservation of Mass

- During transport of a conserved quantity through a finite volume the [ ] or the quantity can only change as the result of an imbalance between the value of the quantity into and out of the volume.

$$F_{in} = F_{out}$$



$$F_{out} = F_{in} + \int_{X_1}^{X_1+\Delta X} \frac{\partial F}{\partial x} dx$$

Mass must be conserved some place: [ ] change in the chamber is a flux divergence.
Sum of all sources and sinks gives the net flux out of the finite volume.

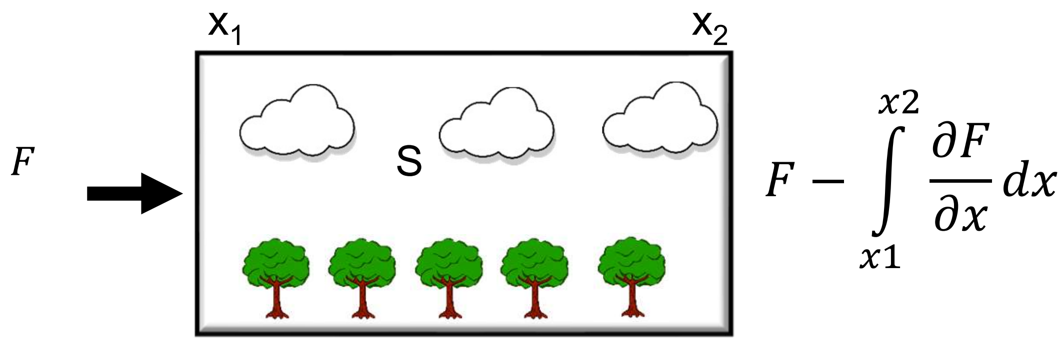
$$F_{in} - \left[F_{in} \pm \frac{\partial F}{\partial x} dx \right] = \frac{\partial c}{\partial t} dx$$

$$-\frac{\partial F_j}{\partial x} = \frac{\partial c_j}{\partial t}$$

Flux Divergence term

Storage Flux Term

Continuity Equation



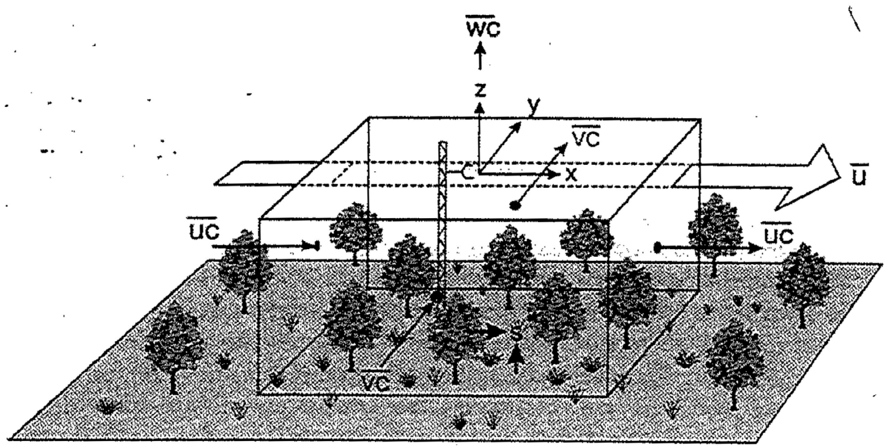
At steady state $\frac{\partial c}{\partial t} = 0$

$$S = -\int_{x1}^{x2} \frac{\partial F}{\partial x} dx$$

Not steady state $\frac{\partial c}{\partial t} \neq 0$

$$S + \frac{\partial c}{\partial t} = -\int_{x1}^{x2} \frac{\partial F}{\partial x} dx$$

1. Compute mass balance over a representative surface control volume.
2. Measure fluxes into and out of the box in all directions along with any accumulation.
3. As CO2 is exchanged between the surface and atmosphere, it can either accumulate/be in deficit (storage) or be transported (advection and turbulence).



Finnigan, 2003

$$NEE = Storage + Transport_{Adv} + Transport_{Turb}$$

$$\frac{\partial c}{\partial t} = \int_0^z \frac{\partial uc}{\partial x} dz + \int_0^z \frac{\partial vc}{\partial y} dz + \int_0^z \frac{\partial wc}{\partial z} dz + \int_0^z \frac{d\bar{c}}{dt} dz \pm S$$

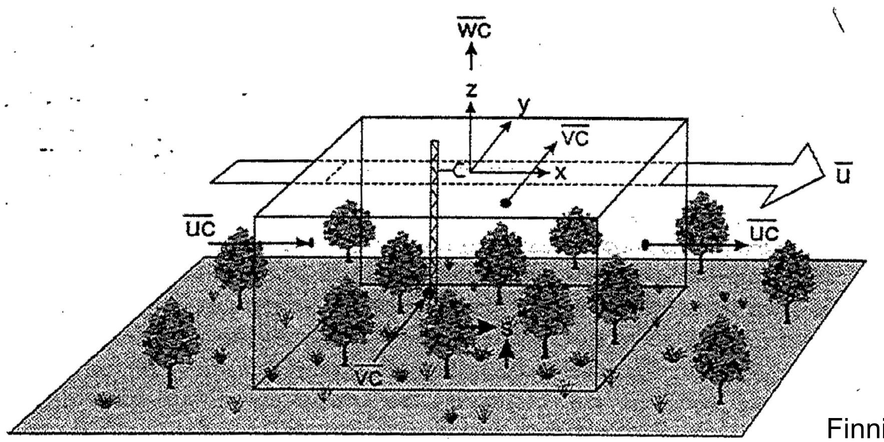
Using Reynolds Averaging

$$S = \int_0^z \frac{\partial \bar{u}\bar{c}}{\partial x} dz + \int_0^z \frac{\partial \bar{v}\bar{c}}{\partial y} dz + \int_0^z \frac{\partial \bar{w}\bar{c}}{\partial z} dz + \int_0^z \frac{\partial \acute{u}\acute{c}}{\partial x} dz + \int_0^z \frac{\partial \acute{v}\acute{c}}{\partial y} + \int_0^z \frac{\partial \acute{w}\acute{c}}{\partial z} + \int_0^z \frac{\partial \bar{c}}{\partial t} dz$$

Mean Turbulent Storage

Reynolds Averaging Rules

1. $\overline{A'} = 0$
2. $\overline{(A + B)} = \bar{A} + \bar{B}$
3. $\overline{\bar{A}B} = \bar{A}\bar{B}$



Finnigan, 2003

Simplify with flat homogenous terrain!

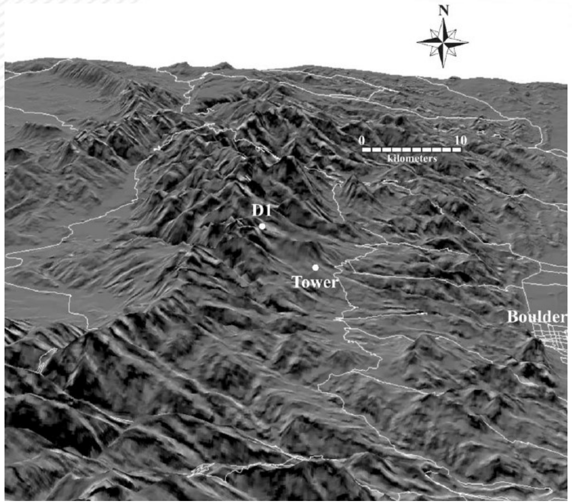
- Horizontal concentration gradients are negligible
- Net horizontal flux is zero
- Measured vertical turbulent flux is representative of the total turbulent flux of the footprint area

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

$$NEE = \int_0^z \frac{\partial \bar{c}}{\partial t} dz + \int_0^z \frac{\partial w'c'}{\partial x}$$

$NEE = \overline{w'c'}$ **for well mixed**

How practical are these assumptions?

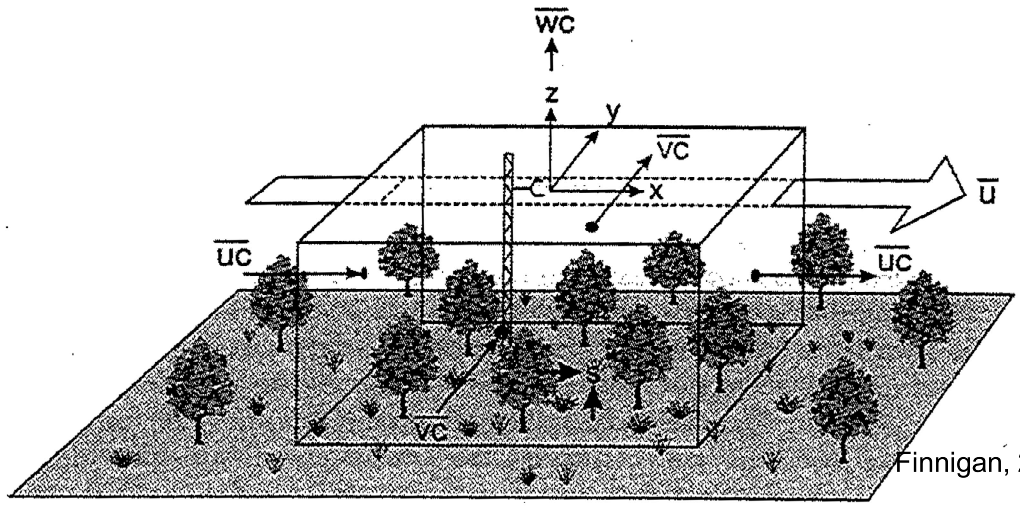


Storage and Advection

http://img.ksl.com/weatherpics/6/609/60925.jpg?filter=ksl/pgallery

- Consider a control volume with a source/sink of a substance X.
- X can either accumulate/be absorbed (storage) or be transported in/out (advection and turbulence)

change in storage = Σ(Flux in) – Σ(Flux out)



Finnigan, 2003

Think about mass balance.

$$NEE = Storage + Transport_{Adv} + Transport_{Turb}$$

How significant is the storage term?

– Depends on BL stability

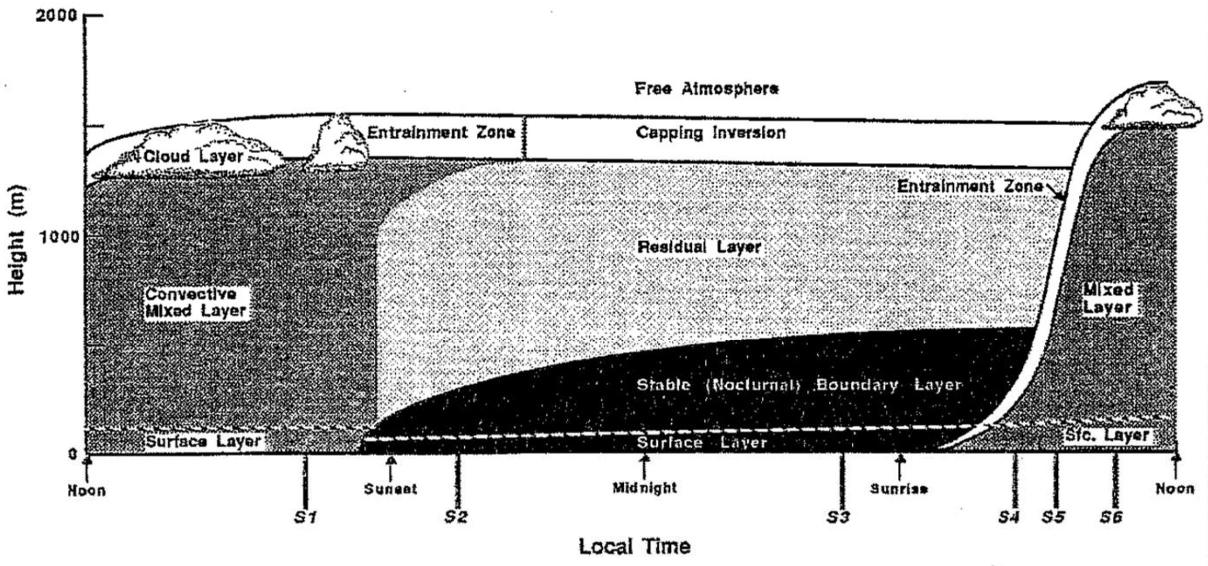


Fig. 1.7 The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer. Time markers indicated by S1-S6 will be used in Fig. 1.12.

Stull, 1988.

- If we integrate over the control volume, we can mathematically describe the net ecosystem exchange of X as:

$$\int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\overline{S_s}\,dzdydz = \int_{-L}^{L}\int_{-L}^{L}\int_{0}^{h_m}\left[\overline{\rho_d}\frac{\partial\chi_s}{\partial t} + \overline{\rho_d u}\frac{\partial\chi_s}{\partial x} + \overline{\rho_d v}\frac{\partial\chi_s}{\partial y} + \overline{\rho_d w}\frac{\partial\chi_s}{\partial z} + \frac{\partial\overline{\rho_d u'\chi_s'}}{\partial x} + \frac{\partial\overline{\rho_d v'\chi_s'}}{\partial y} + \frac{\partial\overline{\rho_d w'\chi_s'}}{\partial z}\right]dzdydz$$

Storage Term — *Advection Transport* — *Turbulent Transport*

Where,

h_m = Measurement height

L = Half the length

S_s = Rate of production/depletion

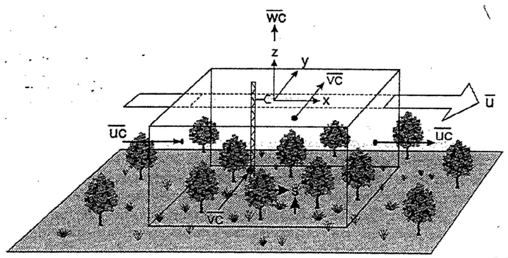
ρ_d = Density of dry air

χ_s = Mixing ratio

u, v, w = Respective x, y, z wind components

' = Fluctuation from the mean

$\bar{}$ = Average value of quantity



As discussed already, if we assume a horizontally homogeneous equilibrium layer, we can imply (Finnigan et al., 2003):

- Horizontal gradients are negligible
- Horizontal integration unnecessary
- Measured mixing ratios and turbulent fluxes are representative of the whole volume

Our equation becomes:

Assume $\overline{w} = 0$

$$NEE = \int_0^{h_m} \overline{\rho_d} \frac{\partial \chi_s}{\partial t} dz + \int_0^{h_m} \overline{\rho_d w} \frac{\partial \chi_s}{\partial z} dz + \overline{\rho_d} \, \overline{w' \chi_s'} \Big|_{h_m}$$

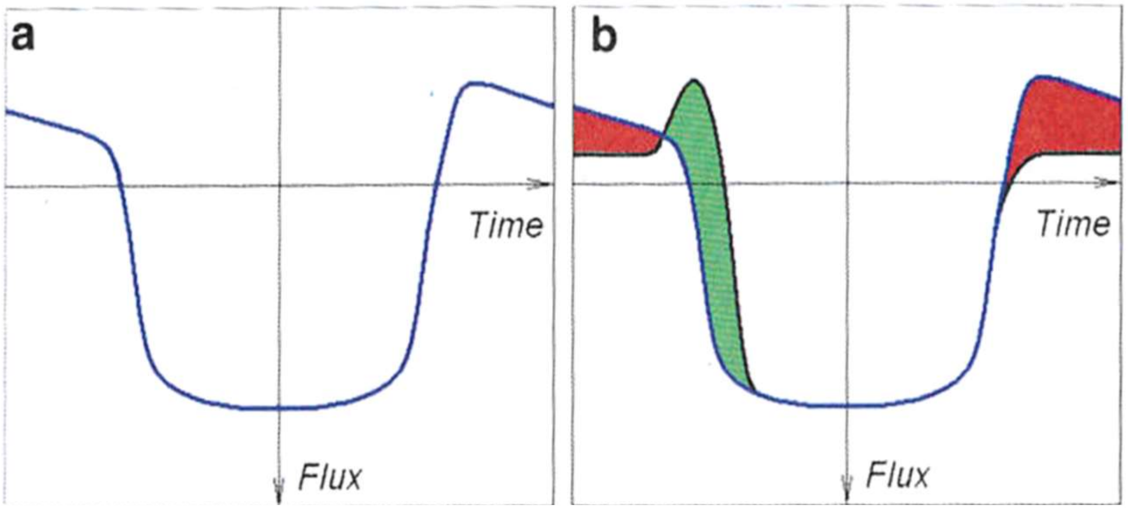
0

Eddy Covariance!!!

Concentration profile measurement!!!

Storage Term | *Vertical Advection* | *Turbulent Transport*

- As conditions become stable, the EC sensors don’t “see” the flux.



Aubinet, 2012

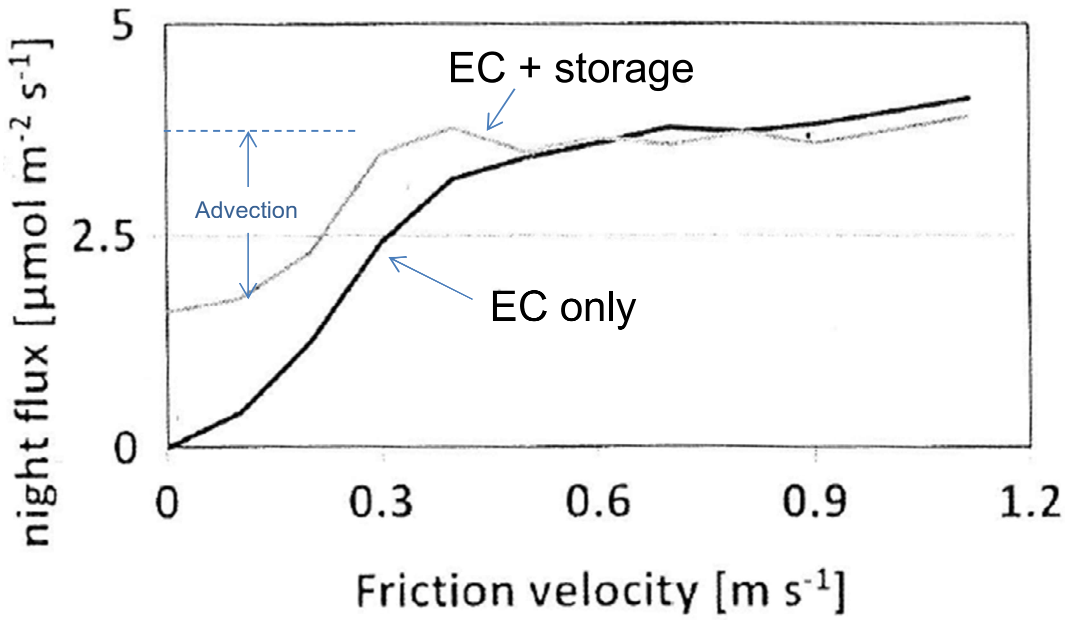
Blue Curve = Actual CO2 Flux, Black Curve = EC measured fluxes

Q: The red area and green area are equal. Does this mean over a 24-hr period EC fluxes will give us accurate net flux?

- A: Yes, in an ideal world, but in the real world, nighttime conditions may lead to:
  - Stratification that decouples surface and measurement system(s)
  - Growing footprint (perhaps into non-homogenous areas)
  - Horizontal gradients develop and advection becomes significant (especially nighttime flows)
  - Non-stationary conditions (sudden changes in concentration and velocity, e.g. nocturnal jets)

Advection is impractical to measure, so it is usually assumed negligible above u* threshold, and is estimated below u* threshold.

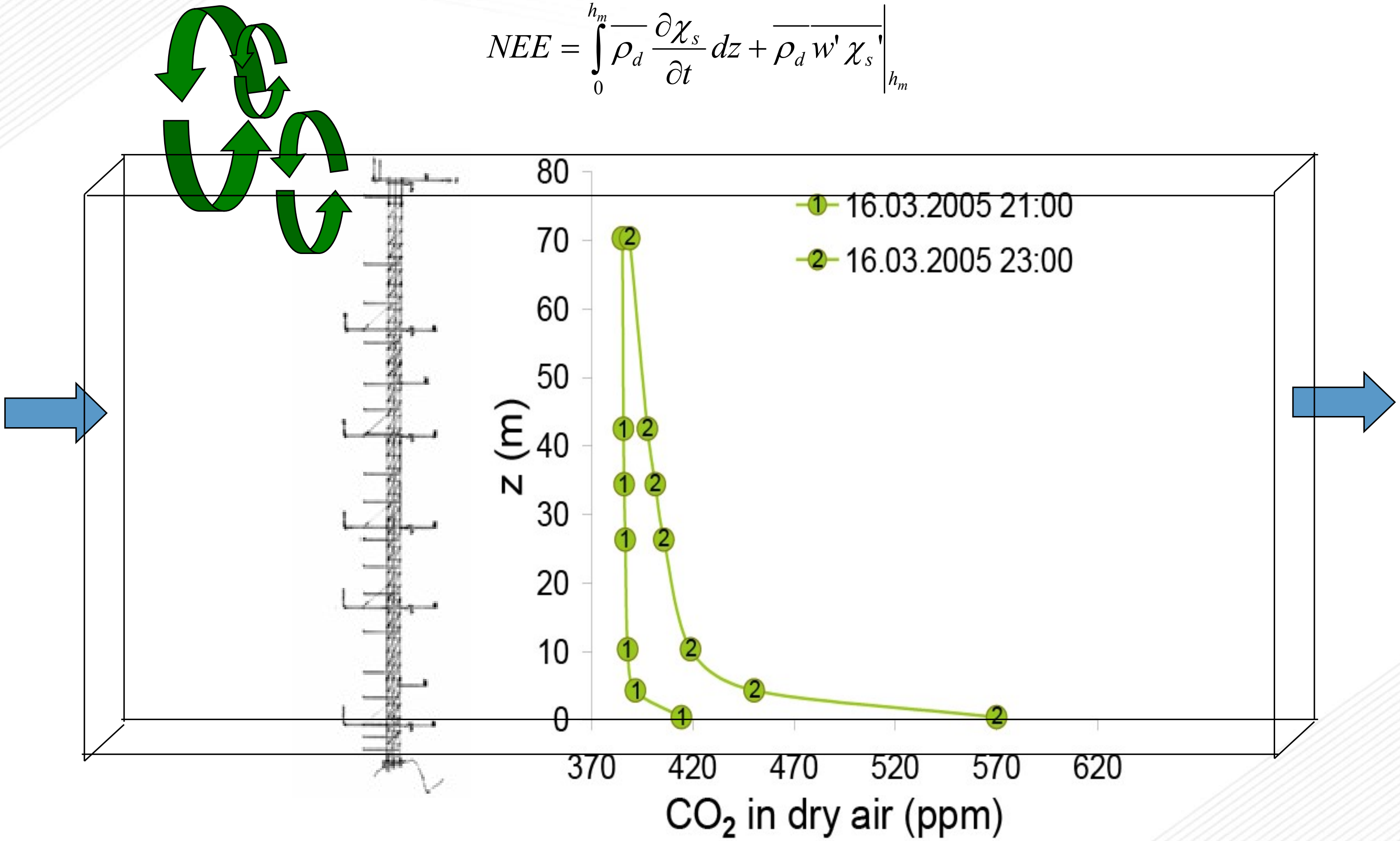
Evidence of Advection



Aubinet et al., 2012

Looking at the real world… An example site from Ray Leuning.

$$NEE = \int_0^{h_m} \overline{\rho_d} \frac{\partial \overline{\chi_s}}{\partial t} dz + \overline{\rho_d}\, \overline{w'\chi_s'} \Big|_{h_m}$$



Slide courtesy of Ray Leuning.