Out of Kansas: Meaningful Turbulence Measurements in Non-Ideal Conditions

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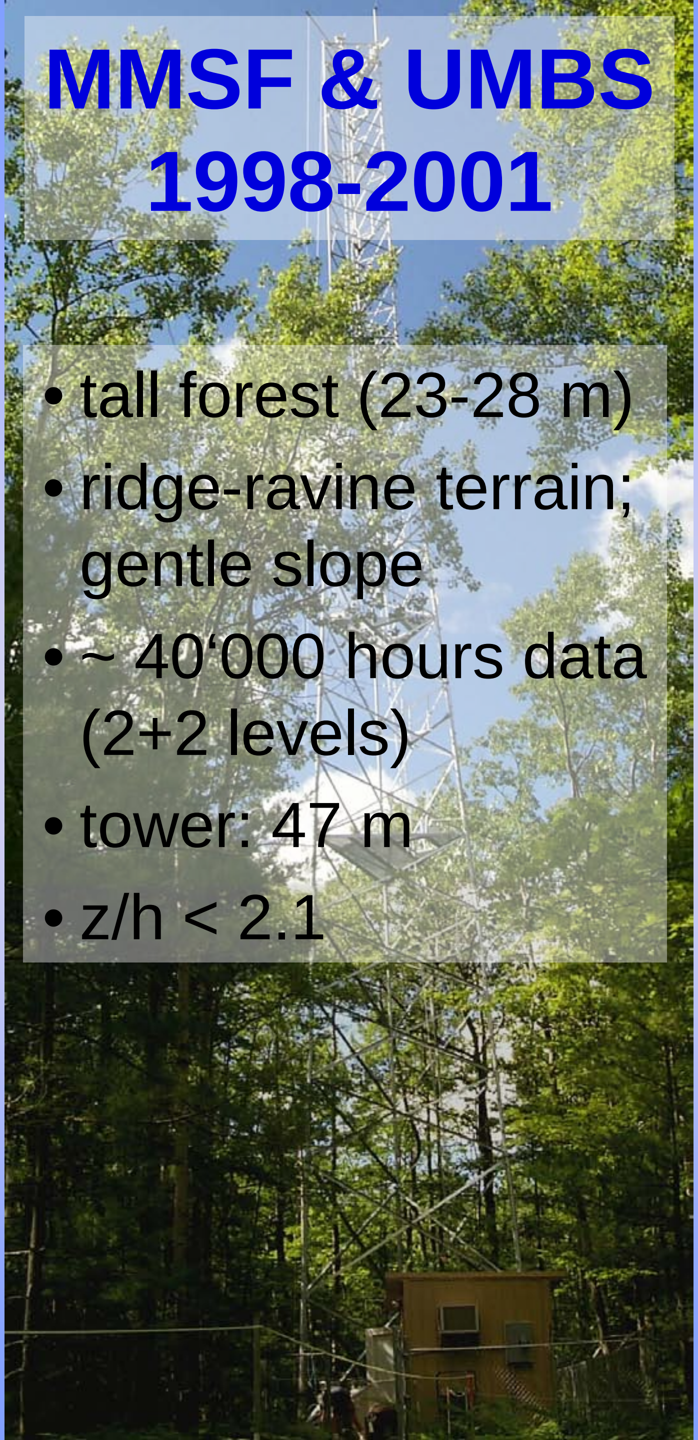
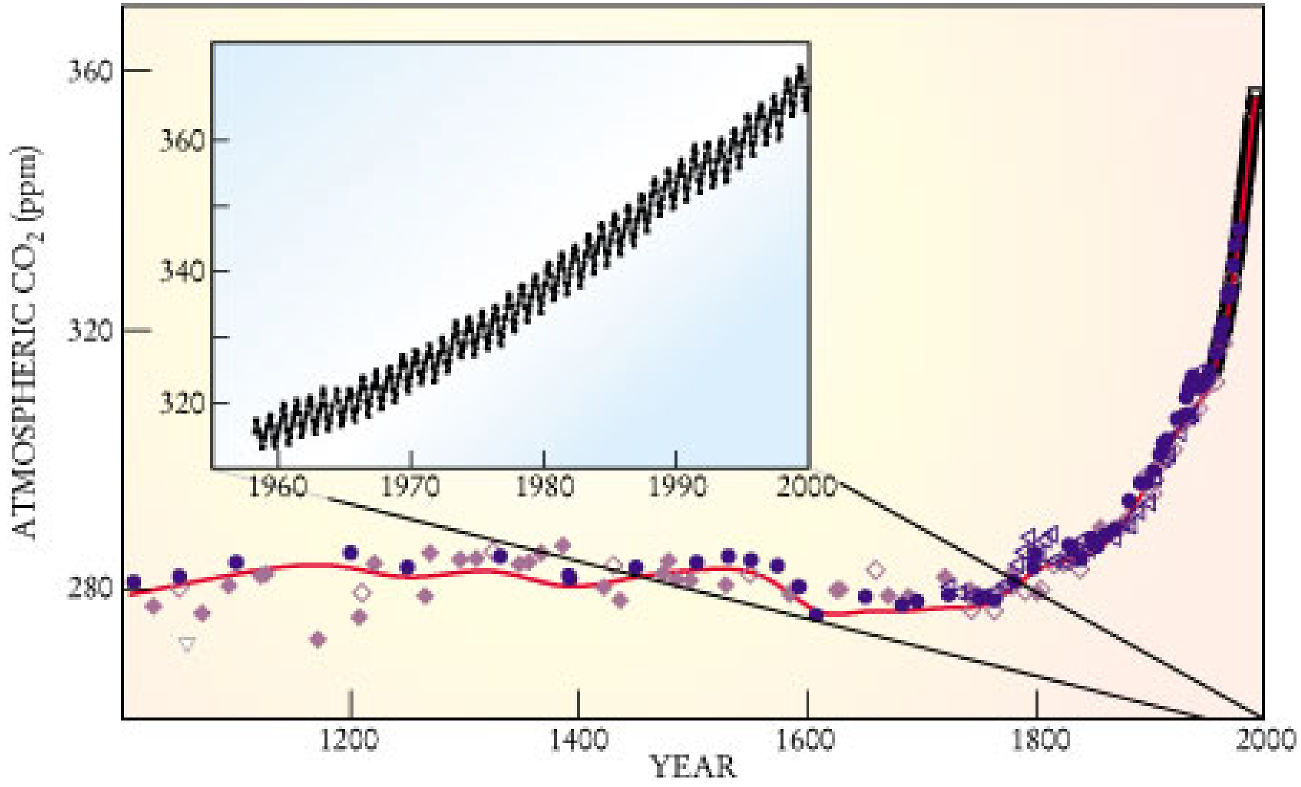
Kansas
1968
• short stubble (20 cm)
• flat, smooth terrain
• 15 hours data
(3 levels)
• tower: 32 m
• z/h > 20-200
Haugen *et al.* 1971 (QJRMS, 97, 168-180)


MMSF & UMBS
1998-2001
• tall forest (23-28 m)
• ridge-ravine terrain; gentle slope
• ~ 40‘000 hours data
(2+2 levels)
• tower: 47 m
• z/h < 2.1

Atmosphere – Biosphere Exchange
Why is it relevant ?

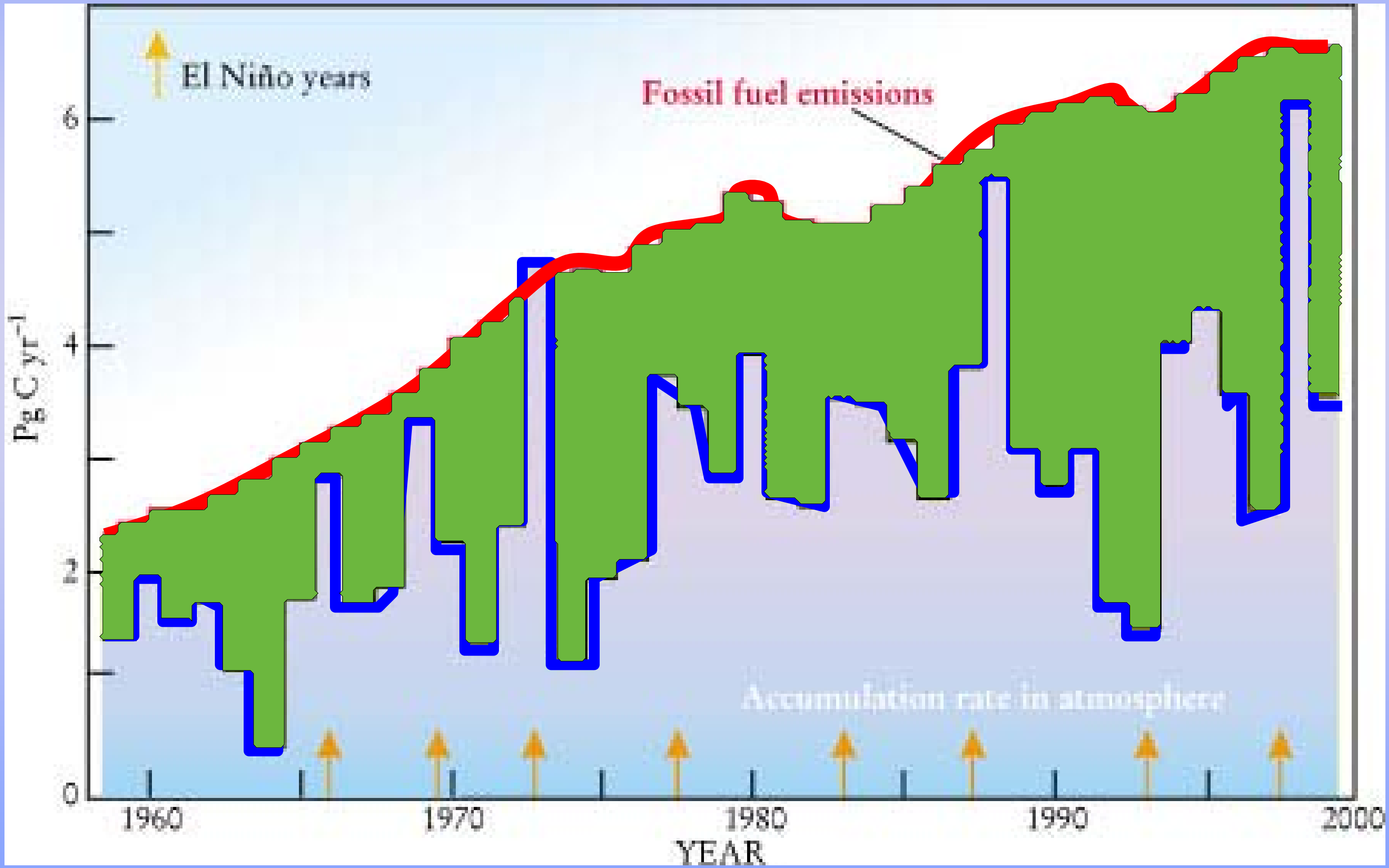
For Example: CO_2



From: *Sarmiento and Gruber,* 2002 (*Phys. Today*)

Background: Global Carbon Budget

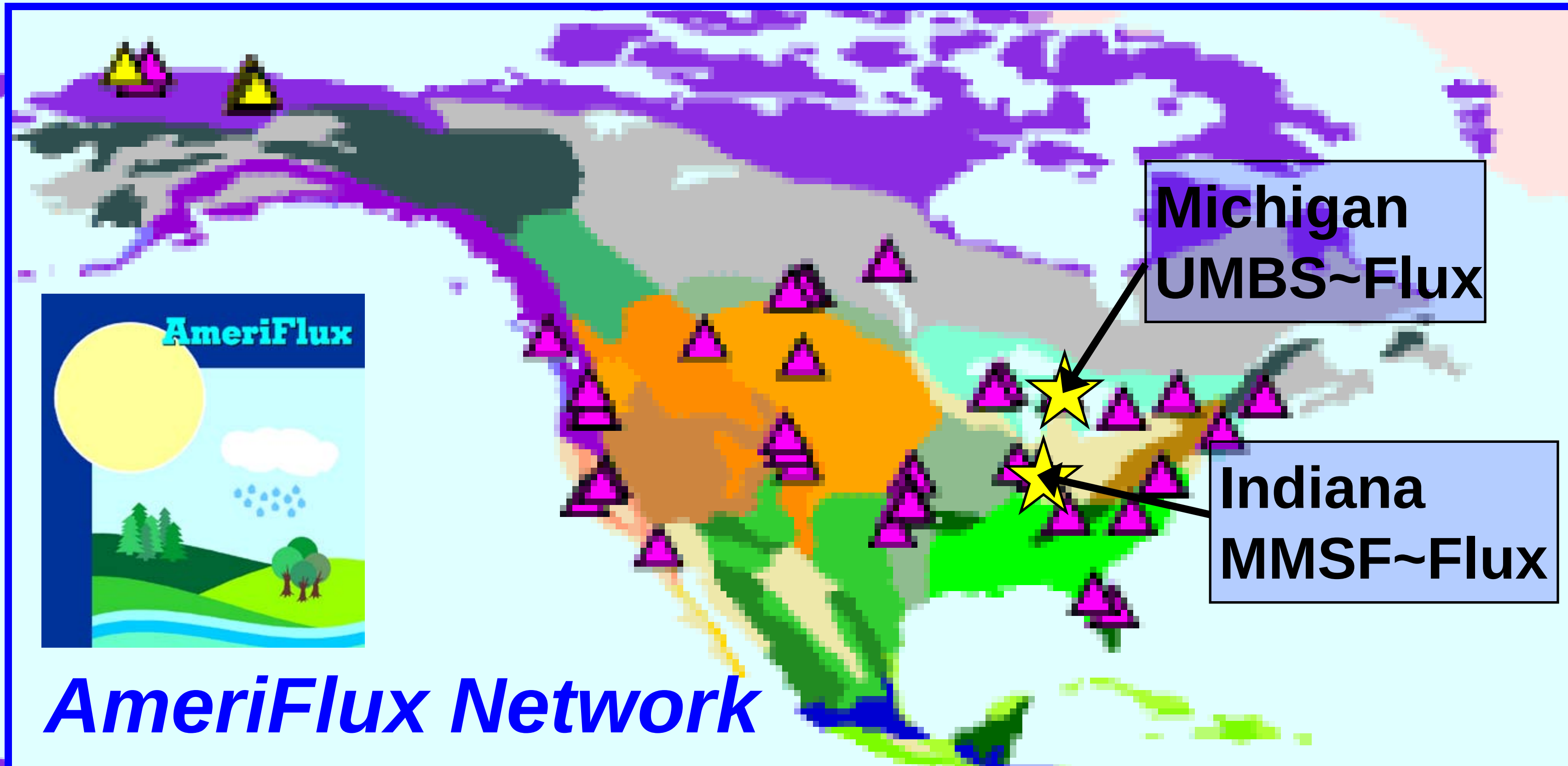
$CO_{2,Atm}$ Accumulation = CO_2 Source - Land & Ocean Sinks



(from Sarmiento and Gruber, 2002)

FLUXNET

Integrating Worldwide
CO_2 Flux Measurements
(currently ~ 300 stations)



Problem: Complex Terrain
Biosphere-Atmosphere Exchange Measurements in "Difficult Conditions"

"Difficult Conditions" ???

⇒ **deviations from micrometeorological ideal:**

Ideal		Deviation
• flat terrain	→	• topography
• homogeneous fetch	→	• patchy land-cover
• low, homogeneous vegetation (if any)	→	• deep, multy-layer vegetation canopy
• stationarity	→	• instationarity
• well-developed turbulence (MOST)	→	• weak turbulence; free convection

Difficult Conditions: Patchy Land Cover

Heterogeneous Scalar Field

(ΔLAI, ΔBowen-Ratio)

Heterogeneous Flow/Turbulence

(disturbance, forest edges)

Difficult Conditions: Deep Canopies

Tall Trees

Multi-Layer Understorey

Difficult Conditions: Topography

Large Scale Topography

Small Scale, Gentle Topography

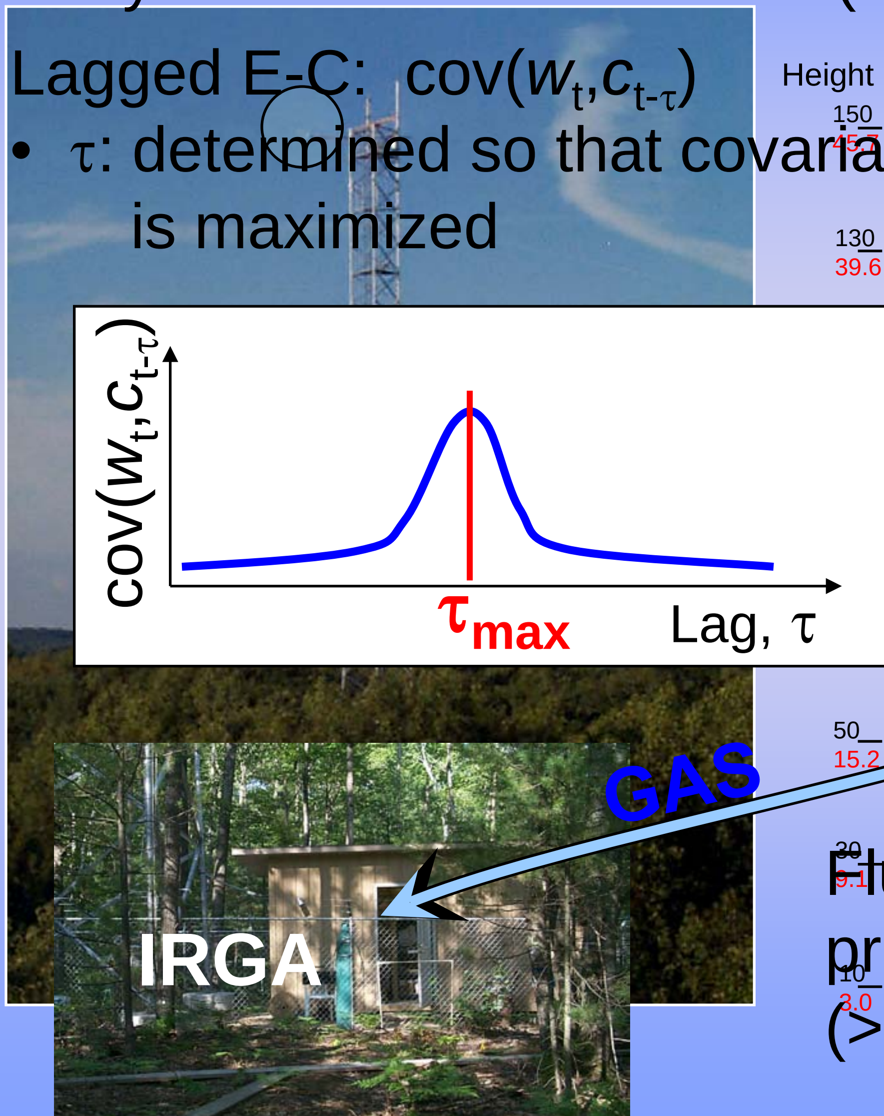
Eddy-Covariance: Closed Path System

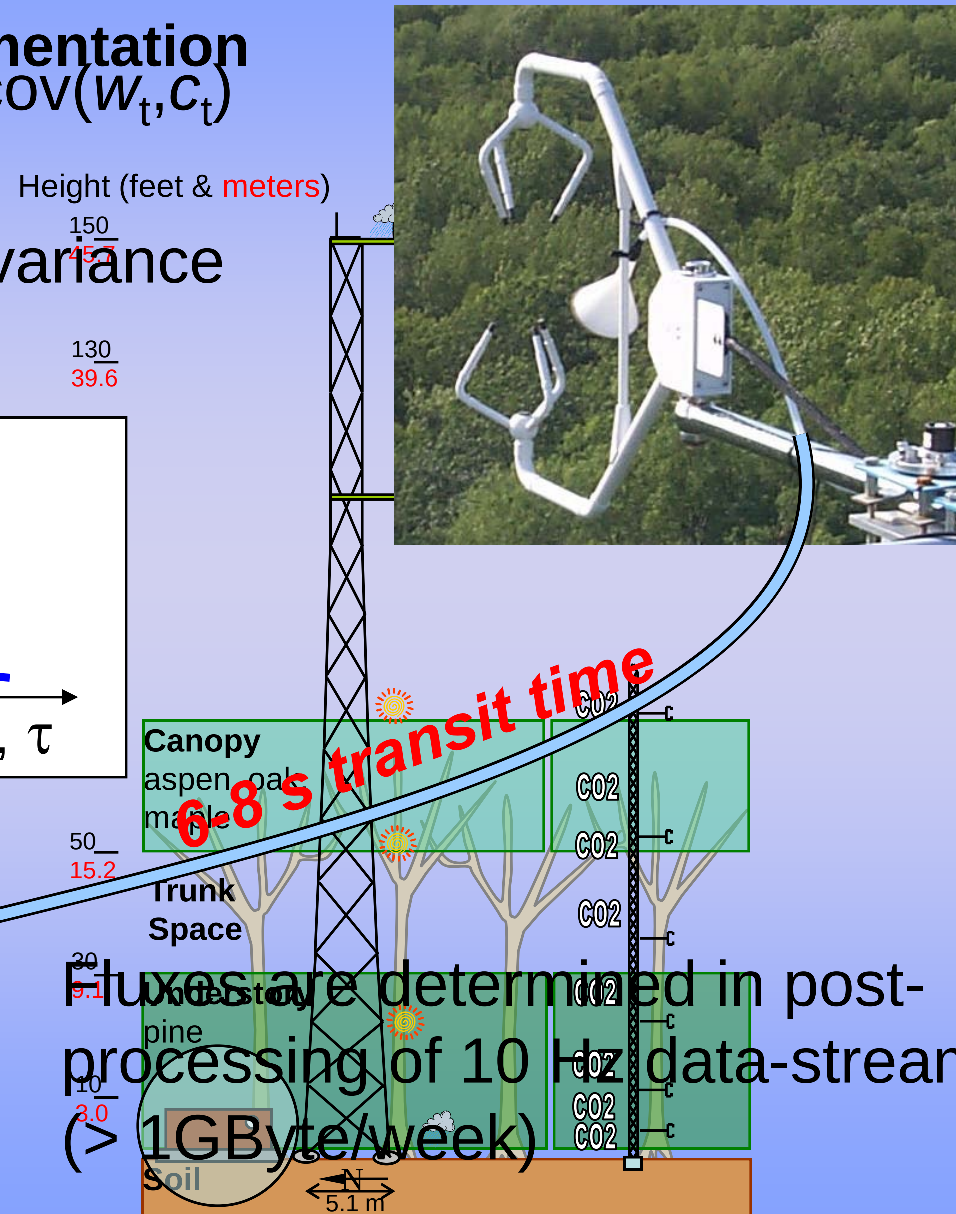
UMBS Flux Tower: Instrumentation

Eddy-Covariance: $\overline{w'c'} = \mathrm{cov}(w_t, c_t)$

Lagged E-C: $\mathrm{cov}(w_t, c_{t-\tau})$

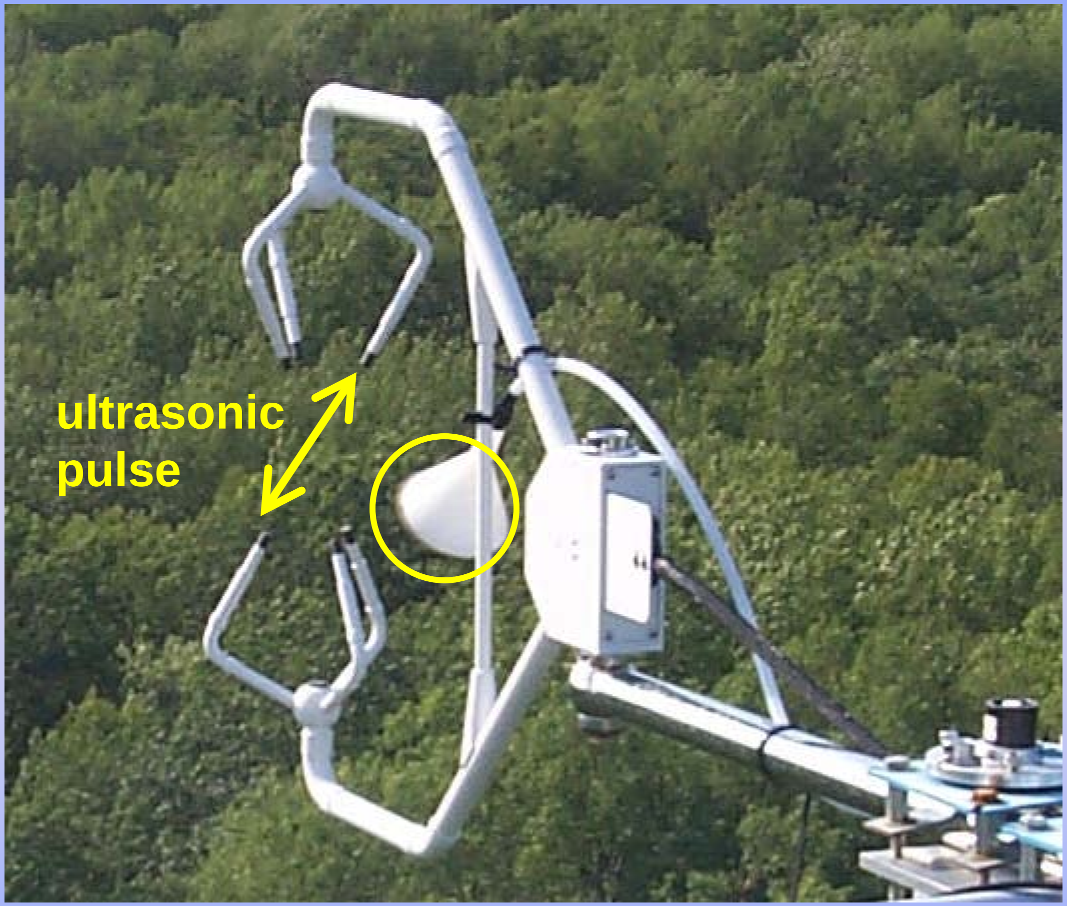
- τ: determined so that covariance is maximized





Fluxes are determined in post-processing of 10 Hz data-stream (> 1GByte/week)

Turbulent Flux: the correlation of eddies



$$\overline{wC} = \overline{w}\,\overline{C} + \overline{w'C'}$$

eddy covariance

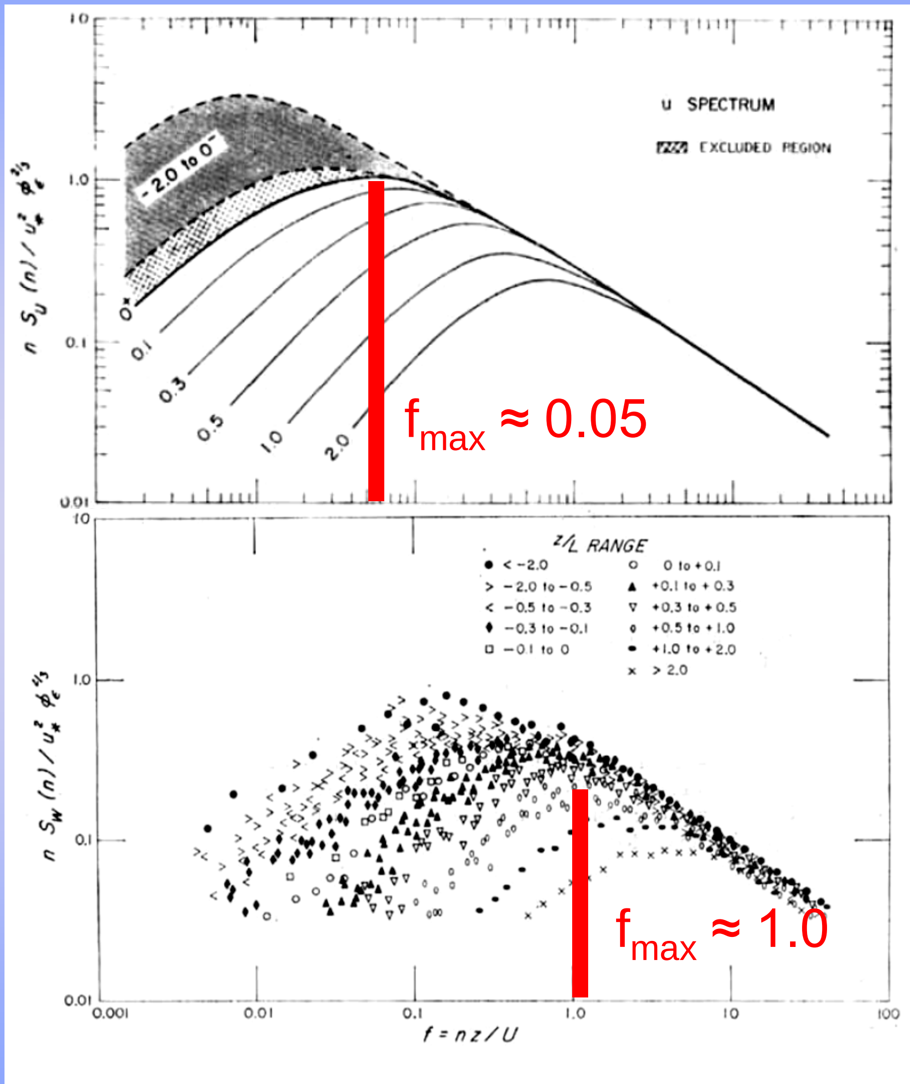
Sonic Anemometer

- measures transit time of ultrasonic pulse $\rightarrow$ depends on air velocity
- fast sampling rate (~10-60 Hz)
- three velocity components
- sonic temperature
- at $\geq$ 10 Hz: resolves most fluctuations in turbulence
- $w = \overline{w} + w'$

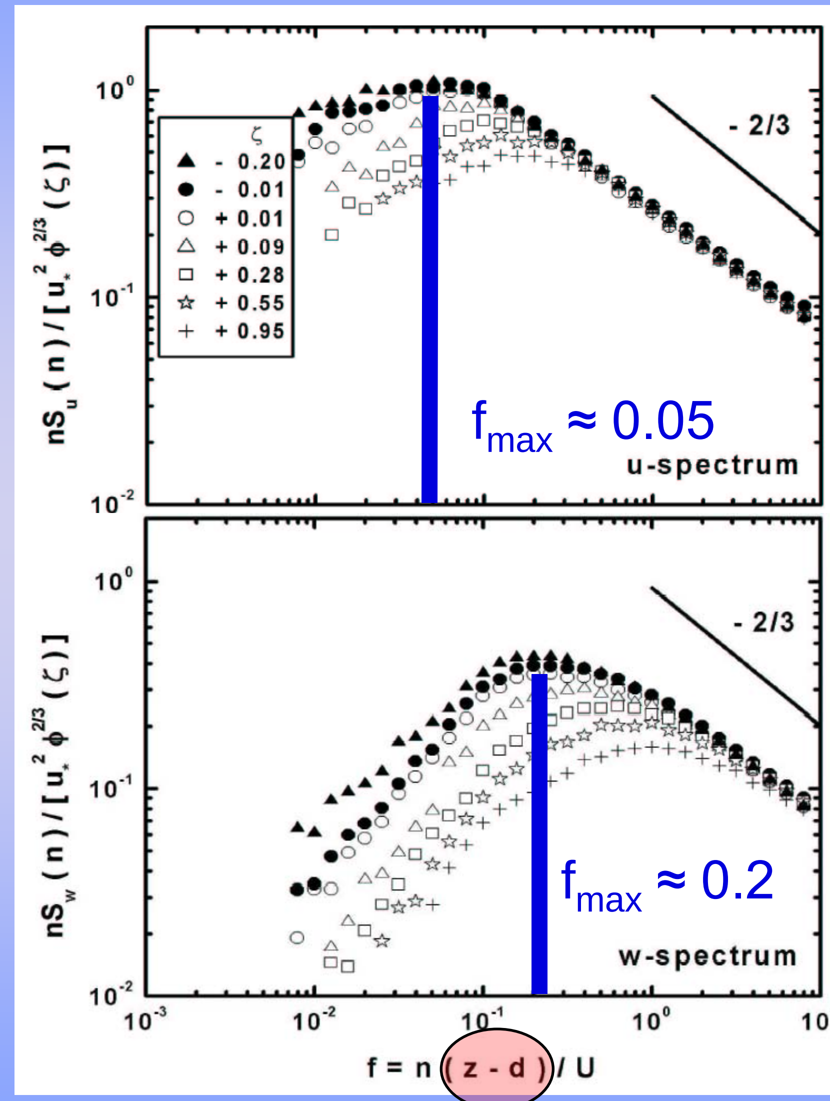
Scalar Concentration

- sample-air intake
- synchronized analysis with sonic signals
- $C = \overline{C} + C'$

Kansas



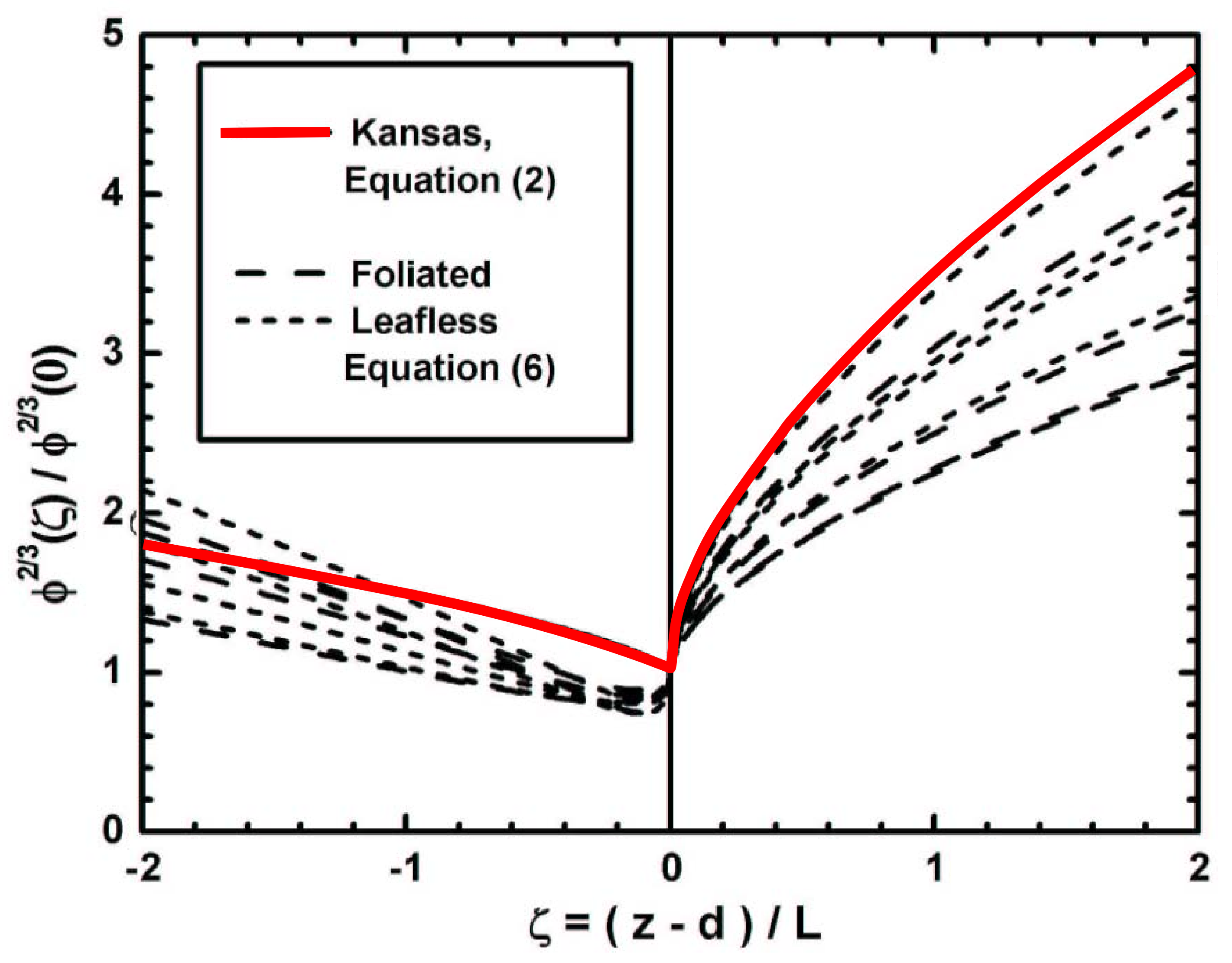
UMBS, 46 m, foliated



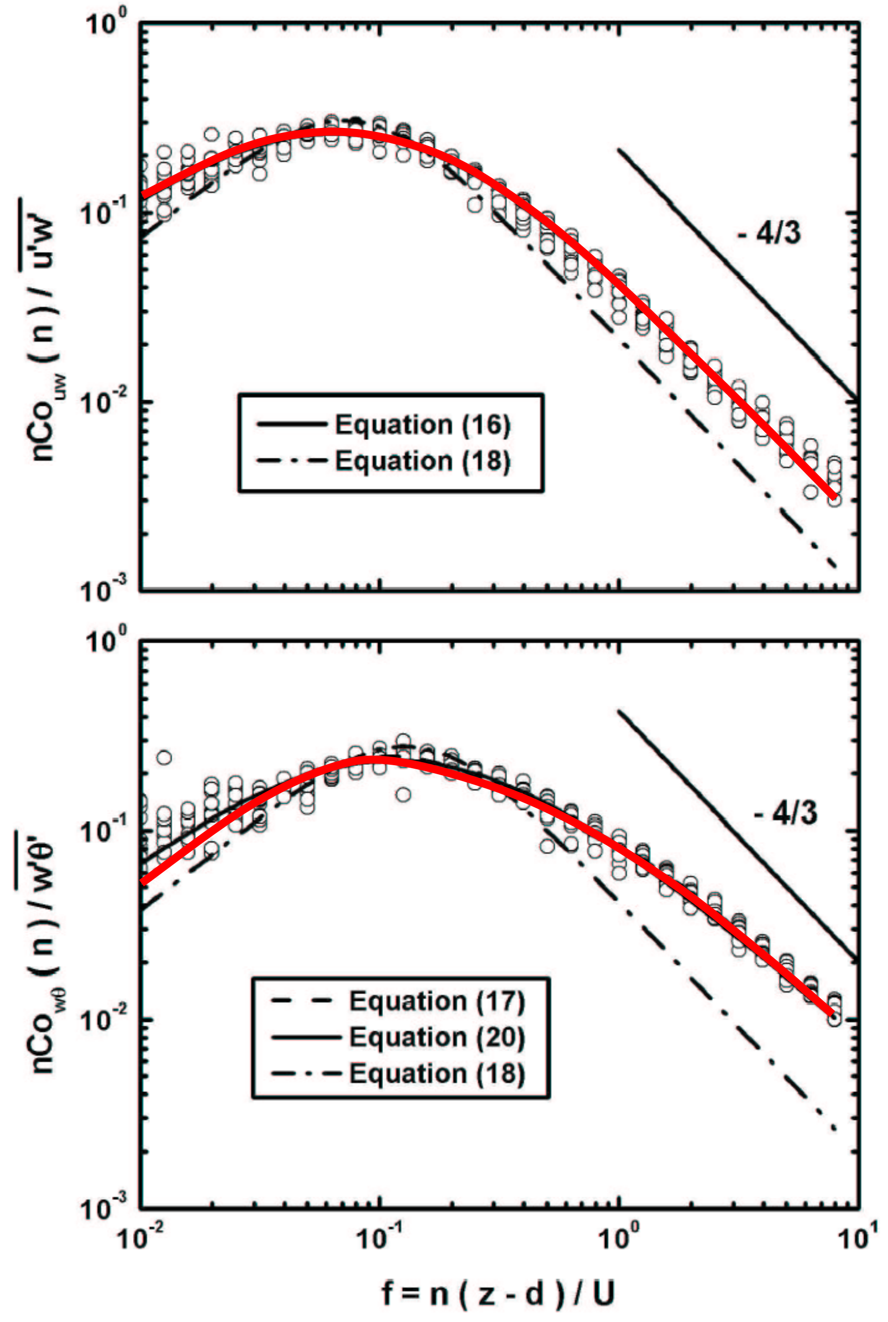
Kaimal *et al. 1972 (QJRMS* **98,** 563–589)

Su *et al. 2004 (BLM* **110,** 213–253)

$$\frac{nS_u(n)}{u_*^2} = \frac{\alpha}{(2\pi k)^{2/3}}\left[\frac{k(z-d)\epsilon}{u_*^2}\right]^{2/3} f^{-2/3} = \frac{\alpha}{(2\pi k)^{2/3}}\phi_\epsilon^{2/3}(\zeta) f^{-2/3}$$



Su *et al. 2004 (Boundary-Layer Meteorol.* **110,** 213–253)

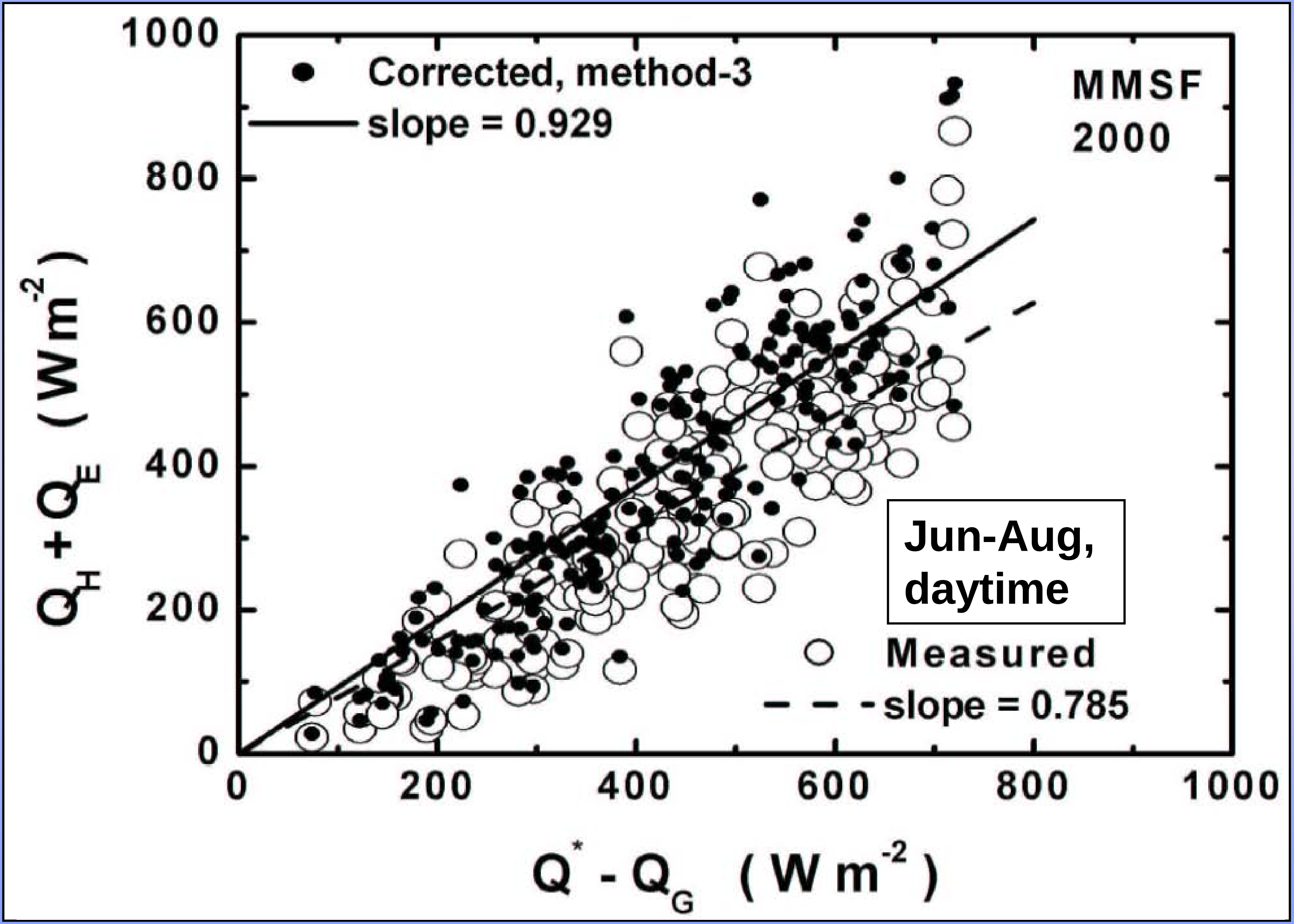


UMBS, 46 m, foliated neutral & unstable:

- co-spectra appear to match well with „smooth“ terrain

Su *et al. 2004 (Boundary-Layer Meteorol.* **110,** 213–253)

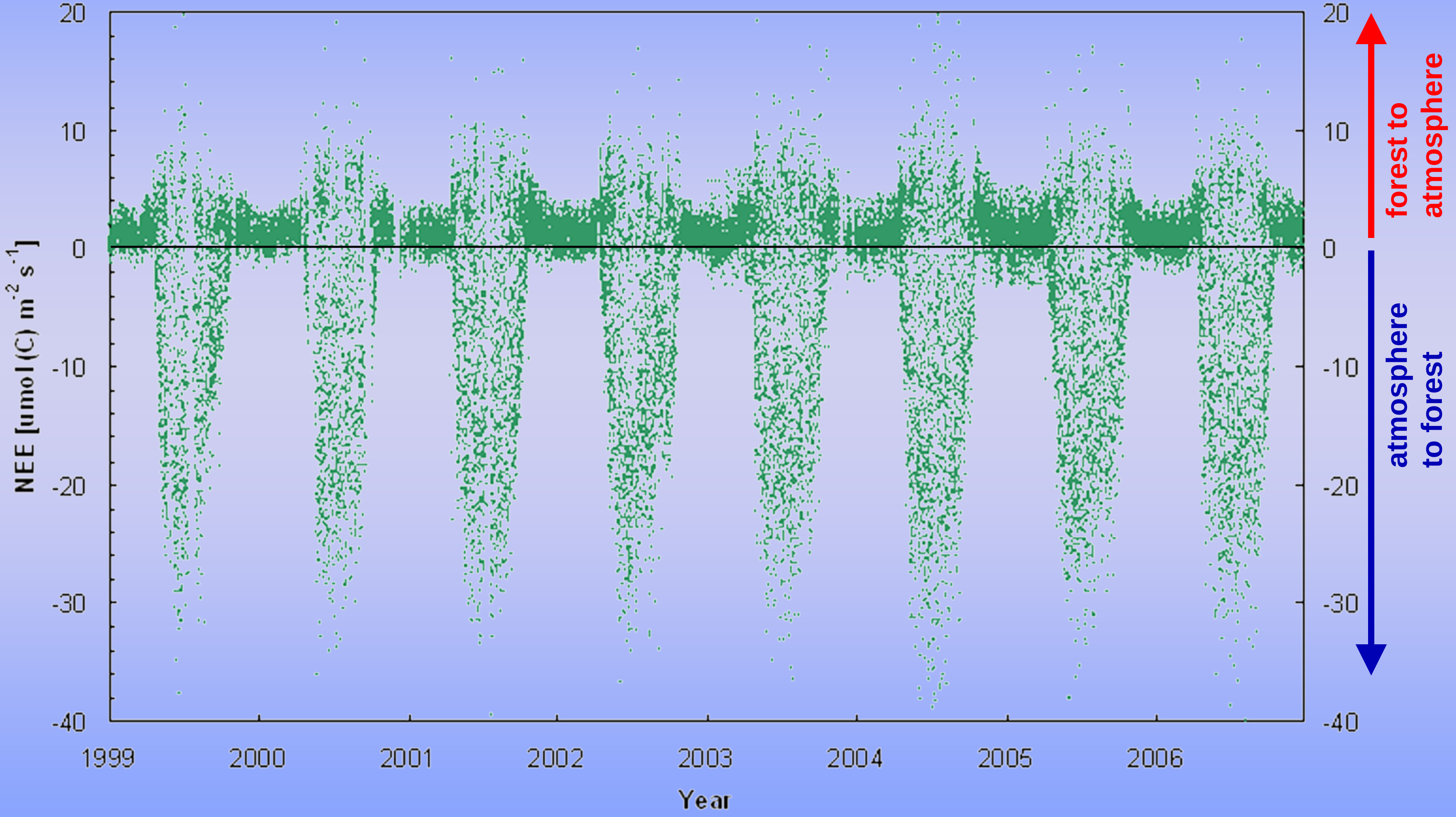
Energy-Balance Closure (after spectral correction)



Su *et al. 2004 (Boundary-Layer Meteorol.* **110,** 213–253)

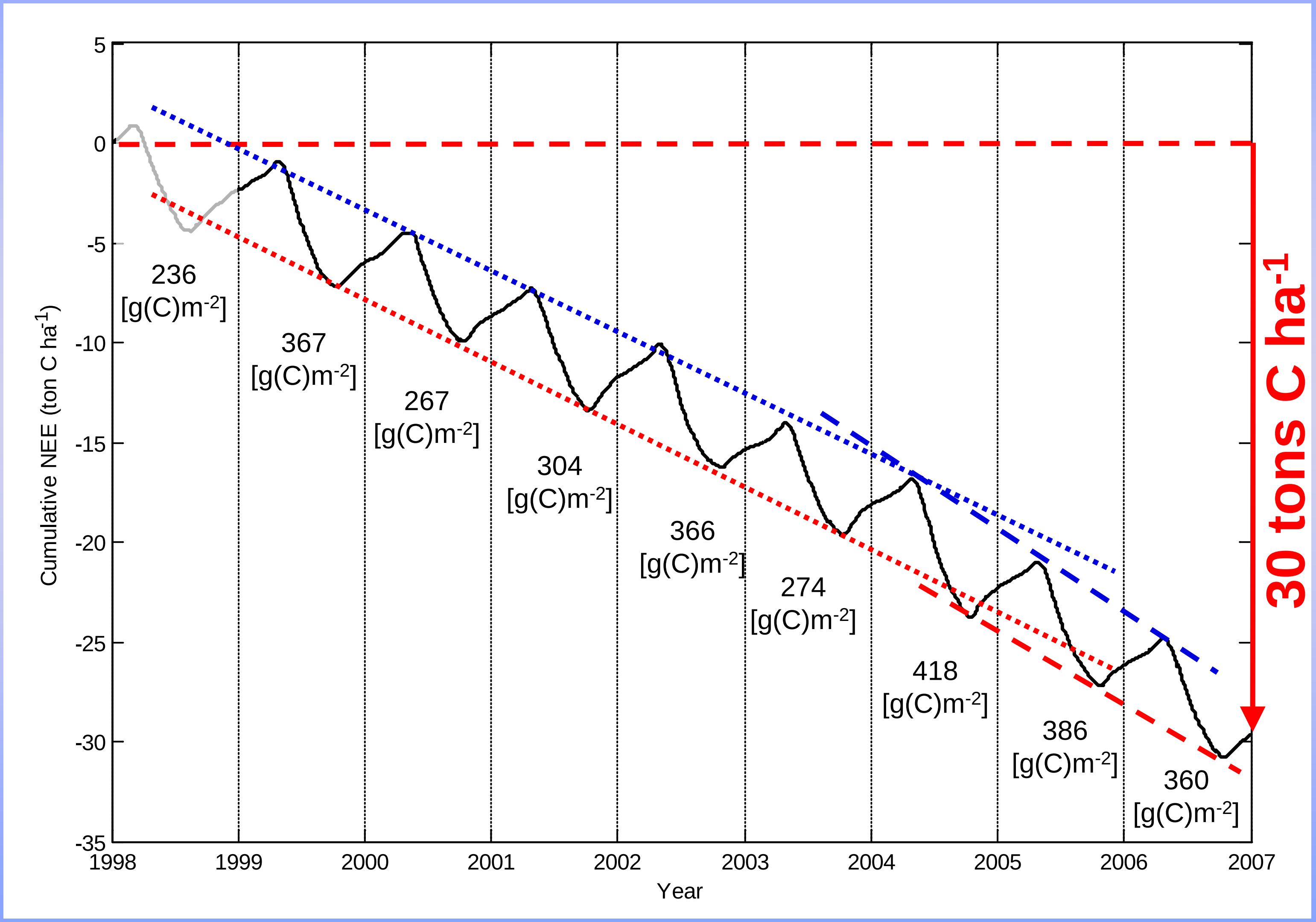
Hourly Fluxes of CO_2 over 8 Years (MMSF)

NEE: *Net Ecosystem Exchange* = Respiration - Assimilation



Cumulative Exchange of CO_2 over 9 Years (MMSF)

NEE: *Net Ecosystem Exchange* = Respiration - Assimilation

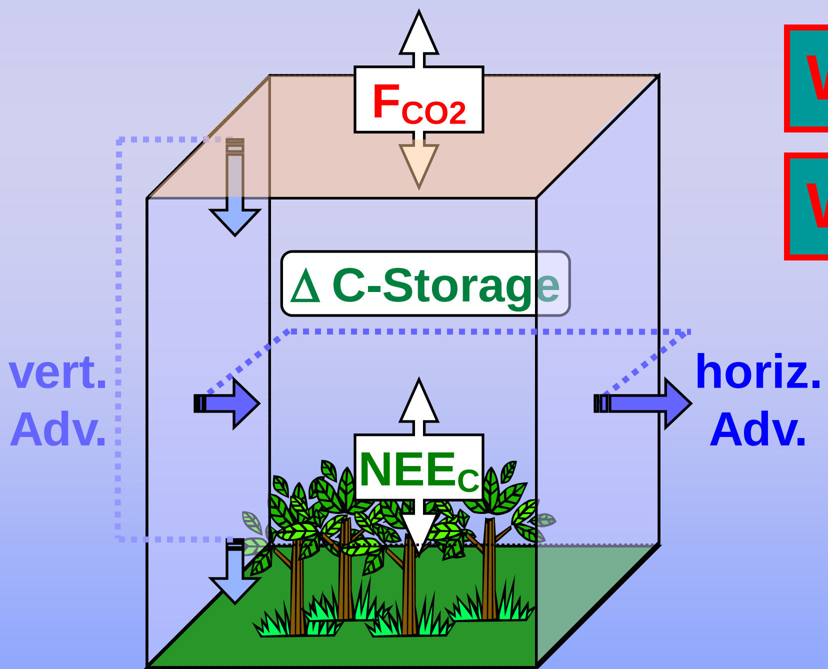


30 tons C ha^{-1} = 3 kg C m^{-2}

Are fluxes capturing the right processes ?

Examine CO_2 Conservation Equation!

$$NEE_C = \frac{z_m}{V} \int_{-\delta x}^{+\delta x} \left(\int_0^{z_m} \left[\frac{\partial \bar{C}}{\partial t} + \bar{u} \frac{\partial \bar{C}}{\partial x} + \bar{w} \frac{\partial \bar{C}}{\partial z} \right] dz + F_C(z_m) \right) \cdot dx$$



What do we want? **NEE !**

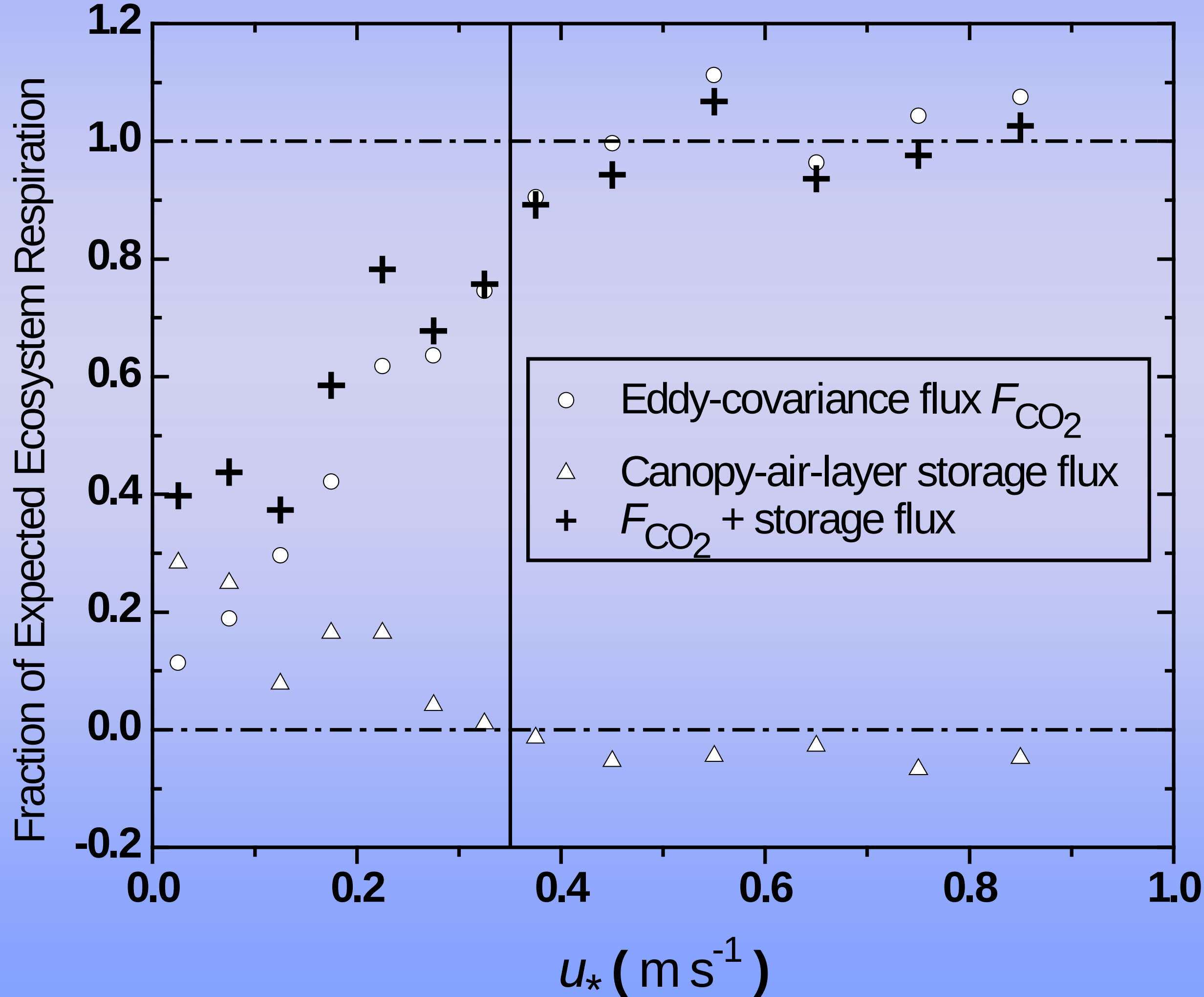
What do we have? **F_C (+ storage)!**

Potential problems:

- location, shape of the box
- “leaking” out of the box

UMBS: Eddy Flux and Storage Term

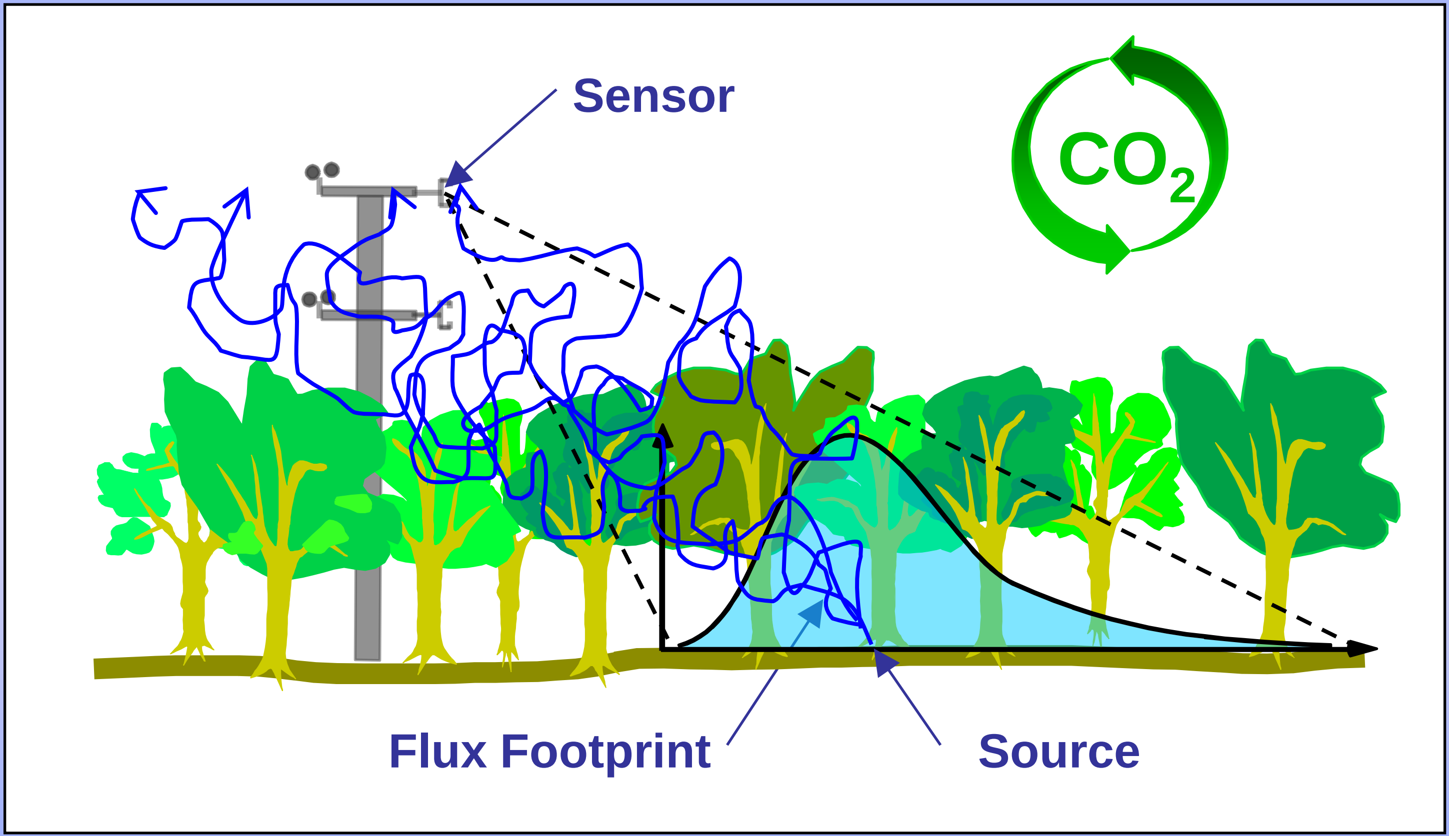
- lack of closure indicates advection important at low u* values



Schmid *et al. 2003 (JGR* **108,** 4417)

Mead rain-fed: land use

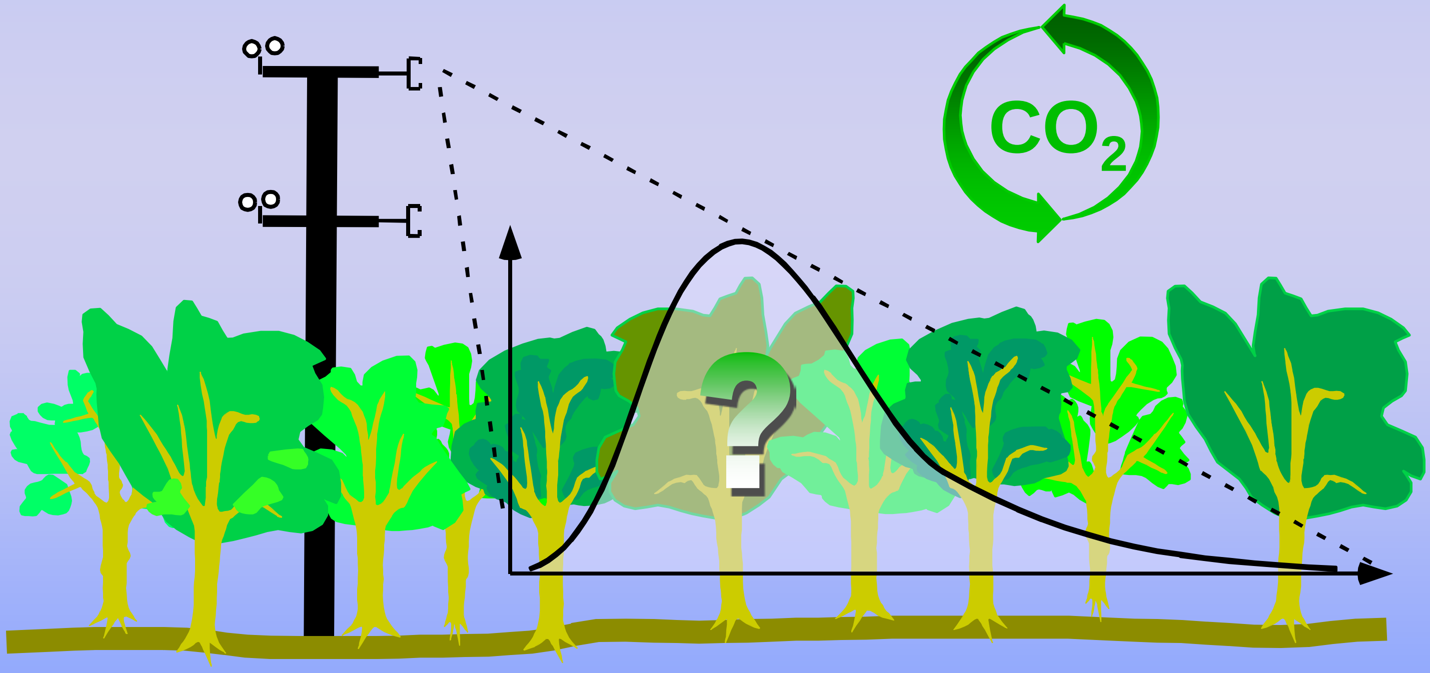
Micrometeorological Flux Measurements:
at what scale?



Schmid 2002 (*Agric. For. Meteorol.* **113**, 159-184)

The Flux Footprint:

- **What Part of the Ecosystem does the Flux Sensor 'see' ?**
- **Is that Part Representative of the Ecosystem? (answer varies over time)**
- **<u>If yes</u>: use data; <u>if not</u>: reject data**

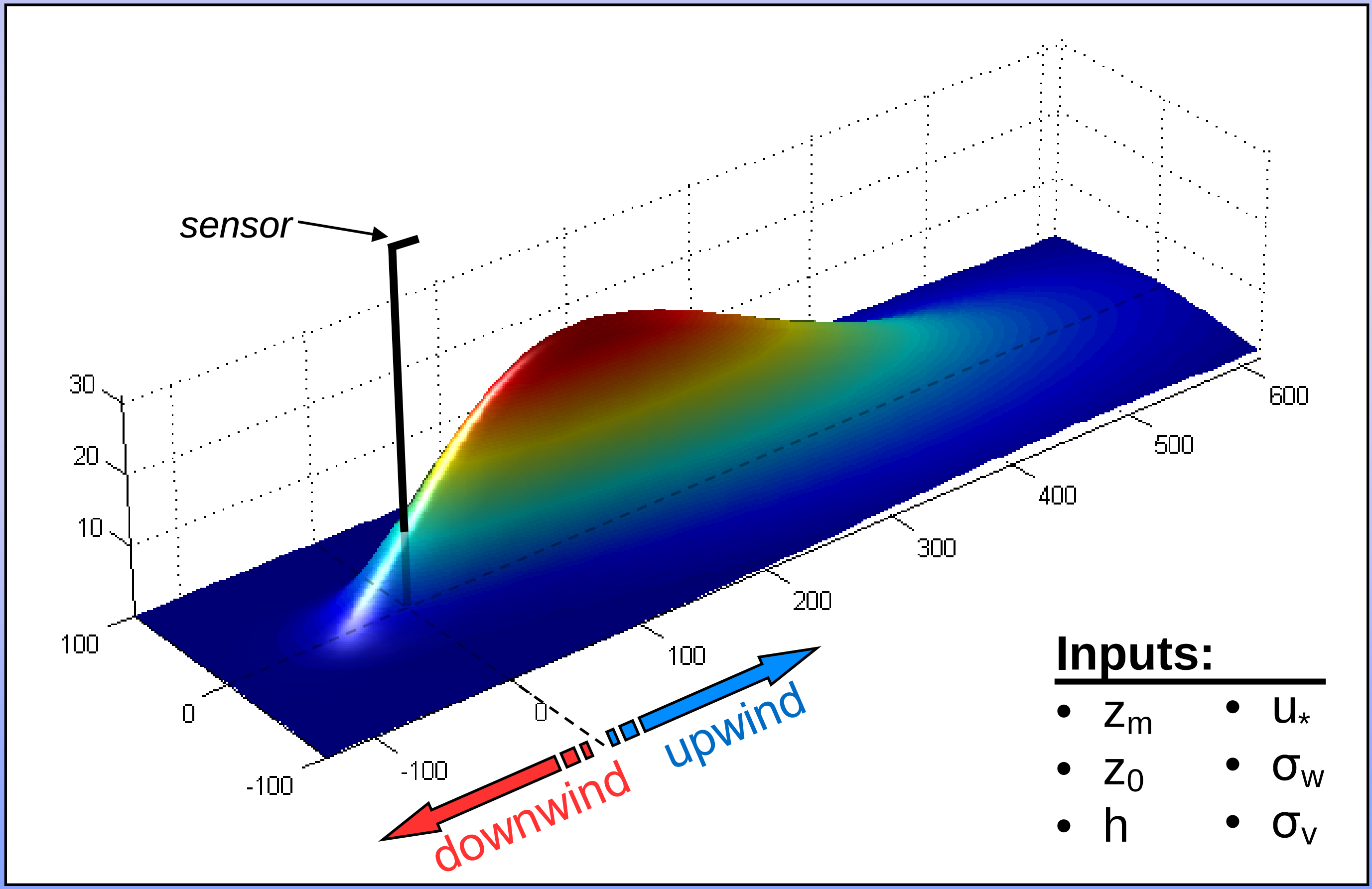


e.g.: Schmid (2002, *Ag. For. Met.*, **113**, 159-184)

Flux Footprint *= spatial* ***filter****, "field of view"*

$$F(\mathbf{x}) = \iint_{\Re} Q_s(\mathbf{x}') \cdot f(\mathbf{x}-\mathbf{x}') \cdot d\mathbf{x}' = Q_s * f$$

(**convolution** of the **source distribution**, ***Q_s***, with the **footprint**, ***f***)



Schmid 1994 (*Boundary-Layer Meteorol.*, **67**, 293-318)

Concentration and Flux Footprint Models

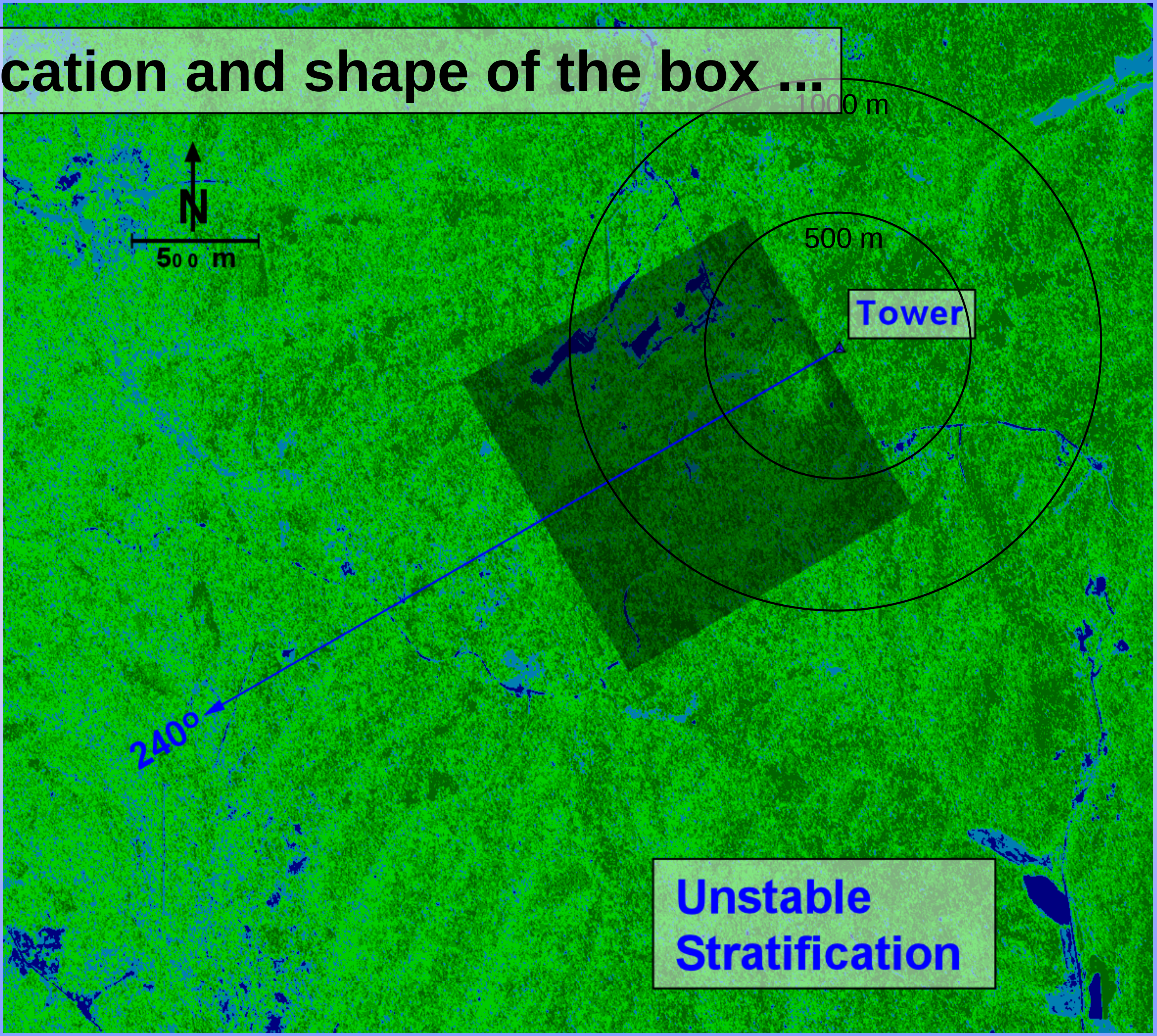
Governing equations in Eulerian analysis:*

	advection		diffusion		forcing	
$\bar{c}$:	$\bar{\mathbf{u}} \cdot \nabla \bar{c}$	+	$\nabla \cdot \left[K_F \frac{\partial \bar{c}}{\partial z} \right]$	=	$Q_S(\mathbf{x})$	← **surface sources**
F:	$\bar{\mathbf{u}} \cdot \nabla F$	+	$\nabla \cdot \left[K_F \frac{\partial F}{\partial z} \right]$	=	$-\overline{\mathbf{u}'^2} \cdot \nabla \bar{c}$	← **flux production rate** (arises from *c*-gradient in turbulent flow). surface sources only in boundary conditions

in inhomogeneous flow, may cause complex behavior of flux footprint

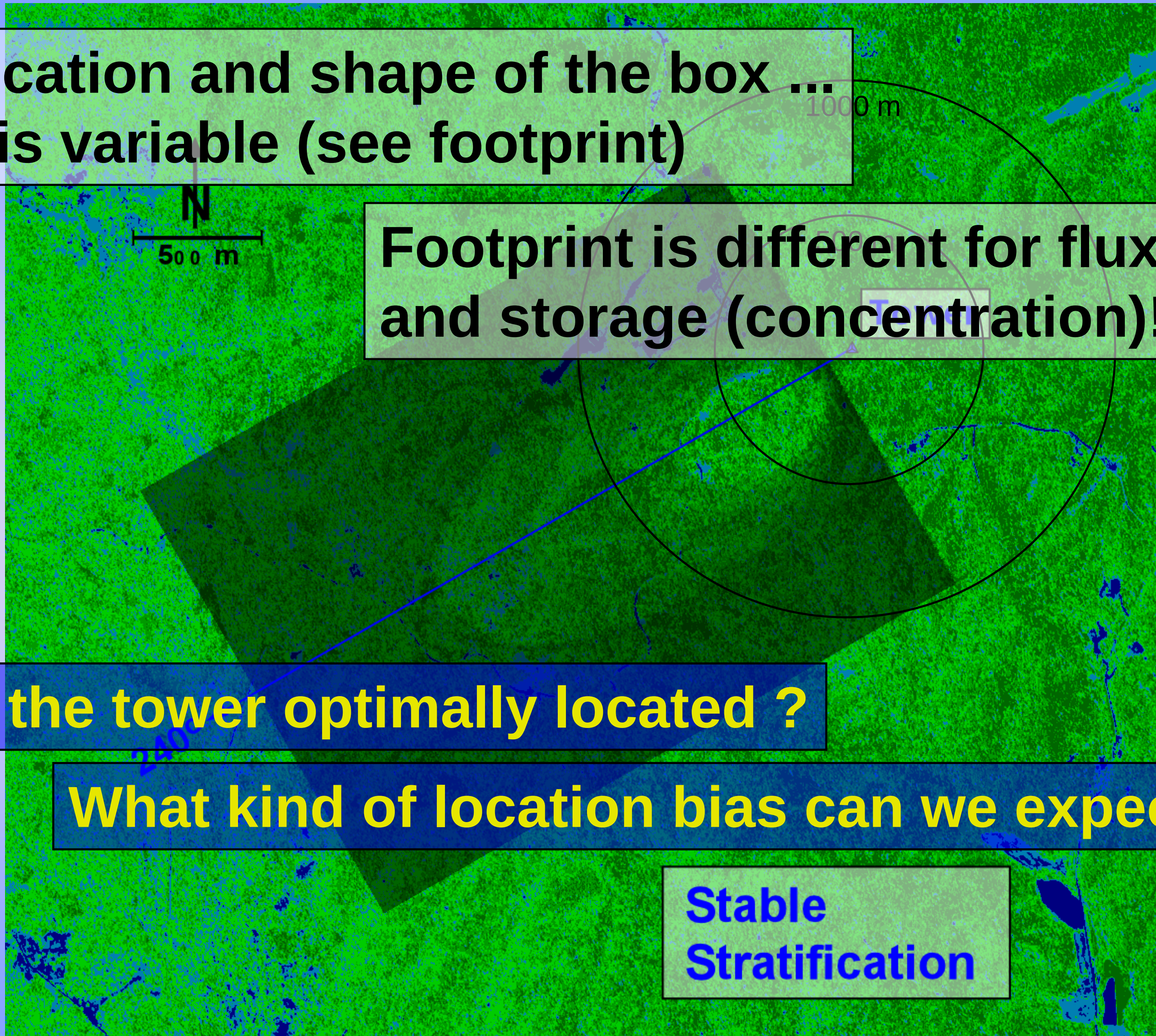
* following Finnigan (2004, AgForMet 127, 117-129); neglecting horizontal turbulent fluxes and pressure interactions.

Location and shape of the box ...



Location and shape of the box ...
... is variable (see footprint)

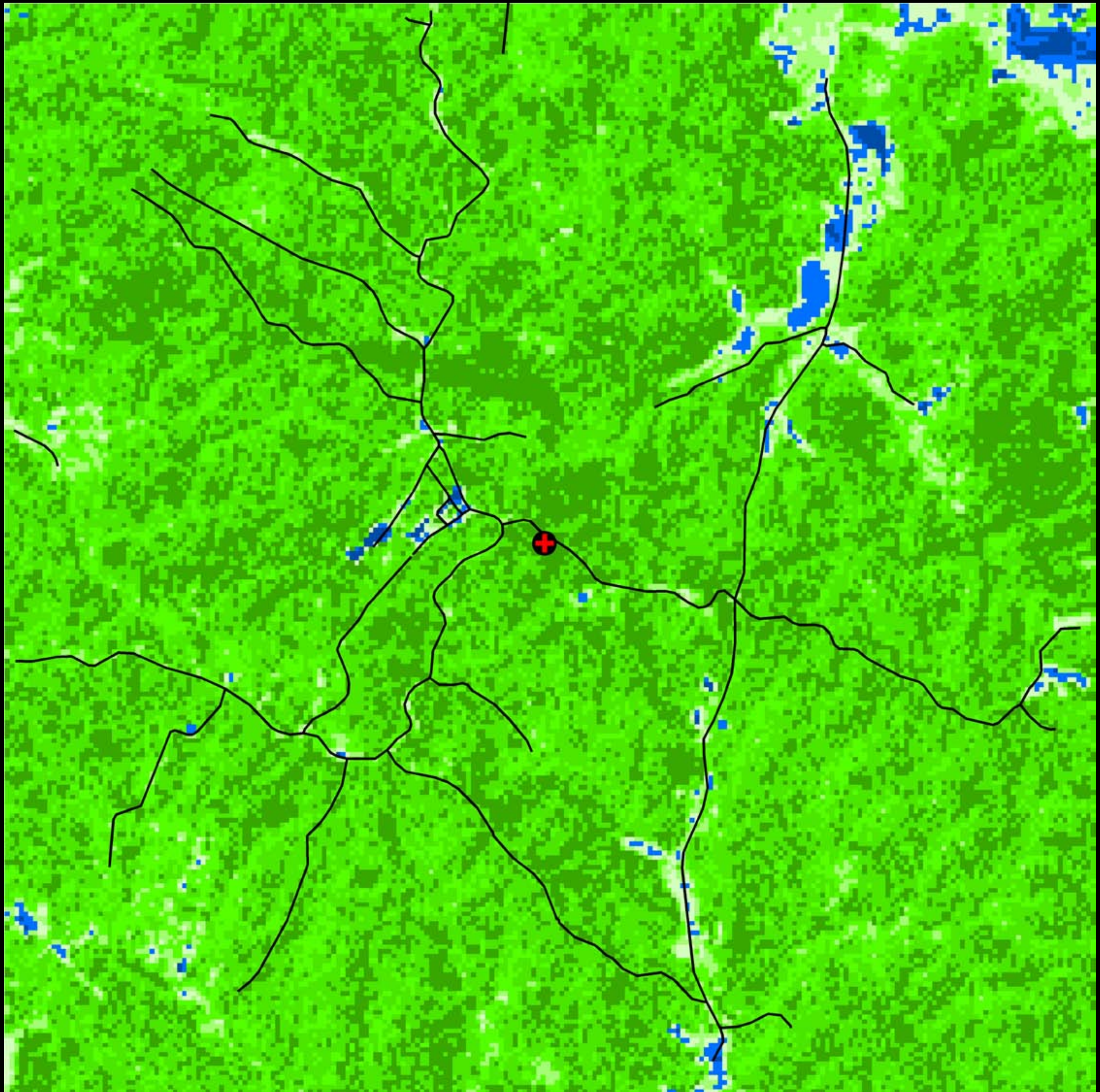
Footprint is different for flux and storage (concentration)!



Is the tower optimally located ?

What kind of location bias can we expect ?

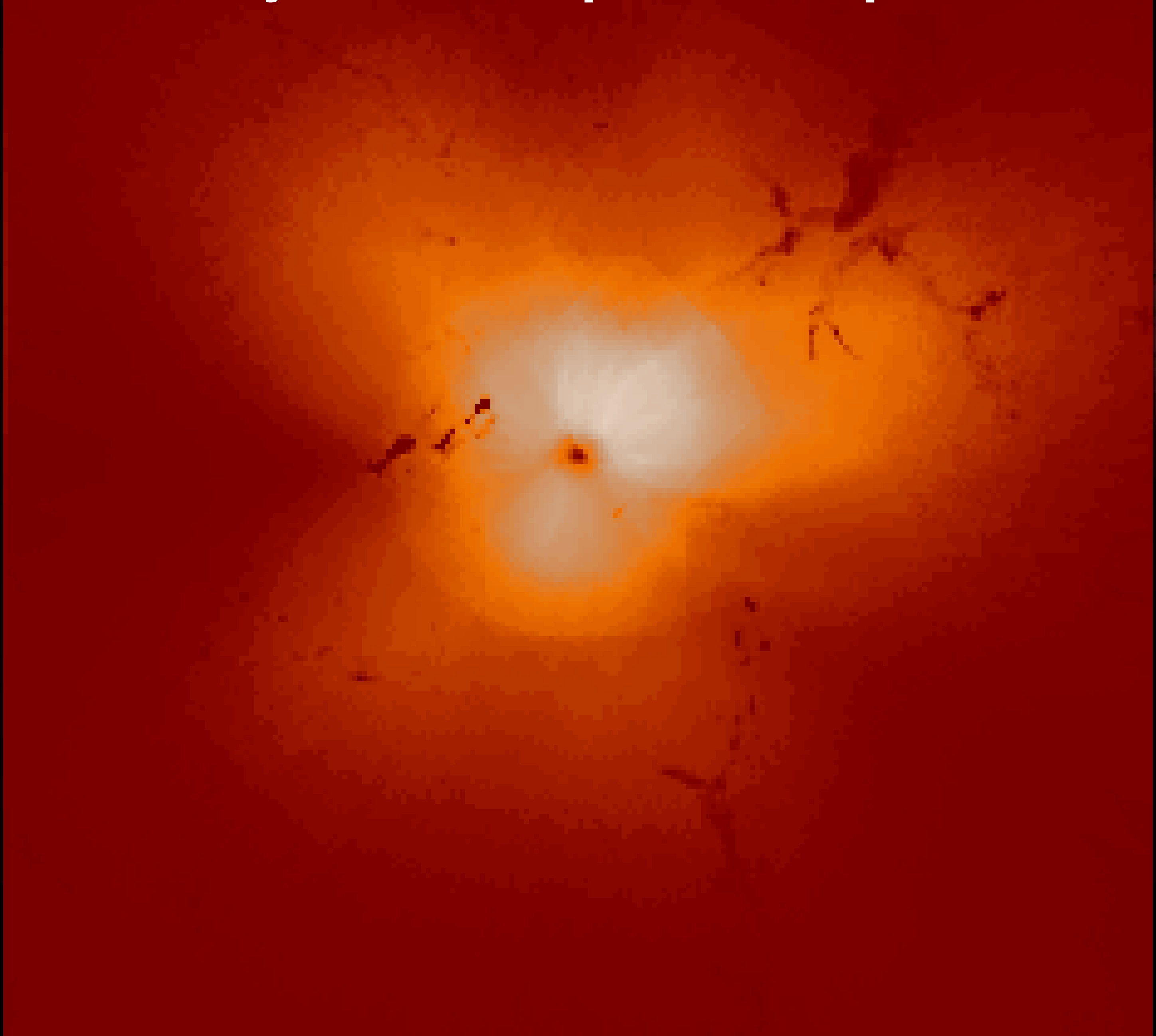
Stable Stratification



Hourly Footprints 2001: YD 217- YD 225

Aug 5 – Aug 13

8-Day Flux Footprint Composite



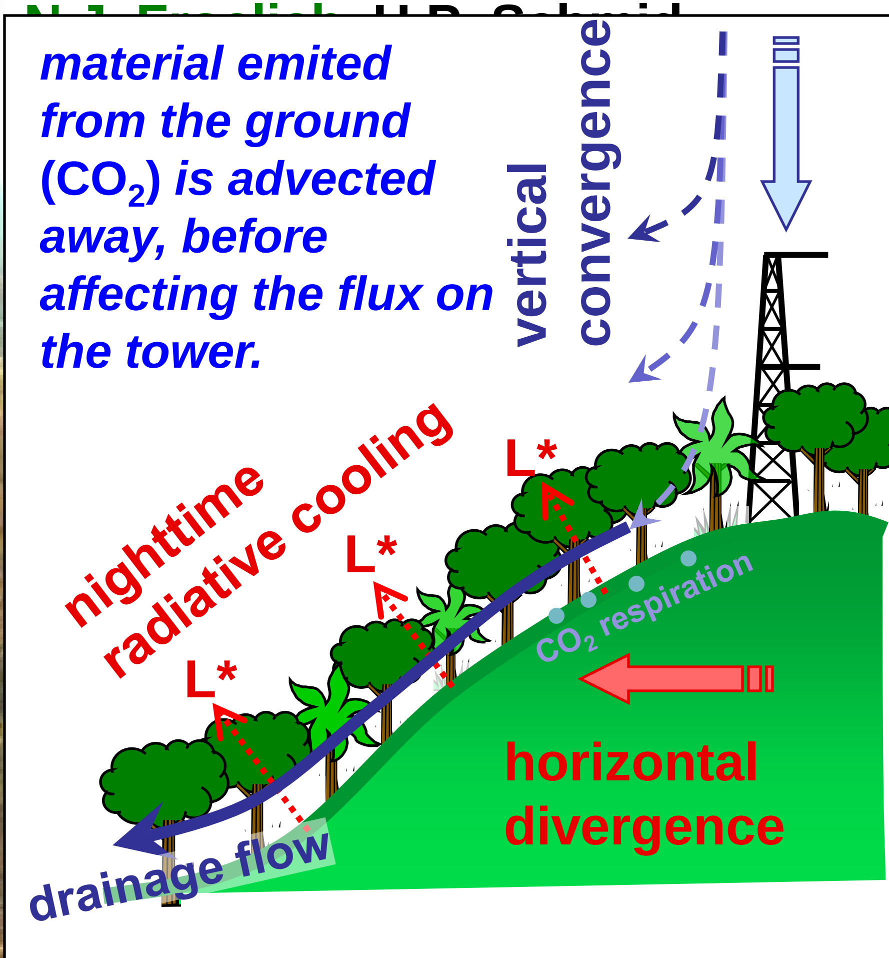
Hourly Footprints 2001: YD 217- YD 225

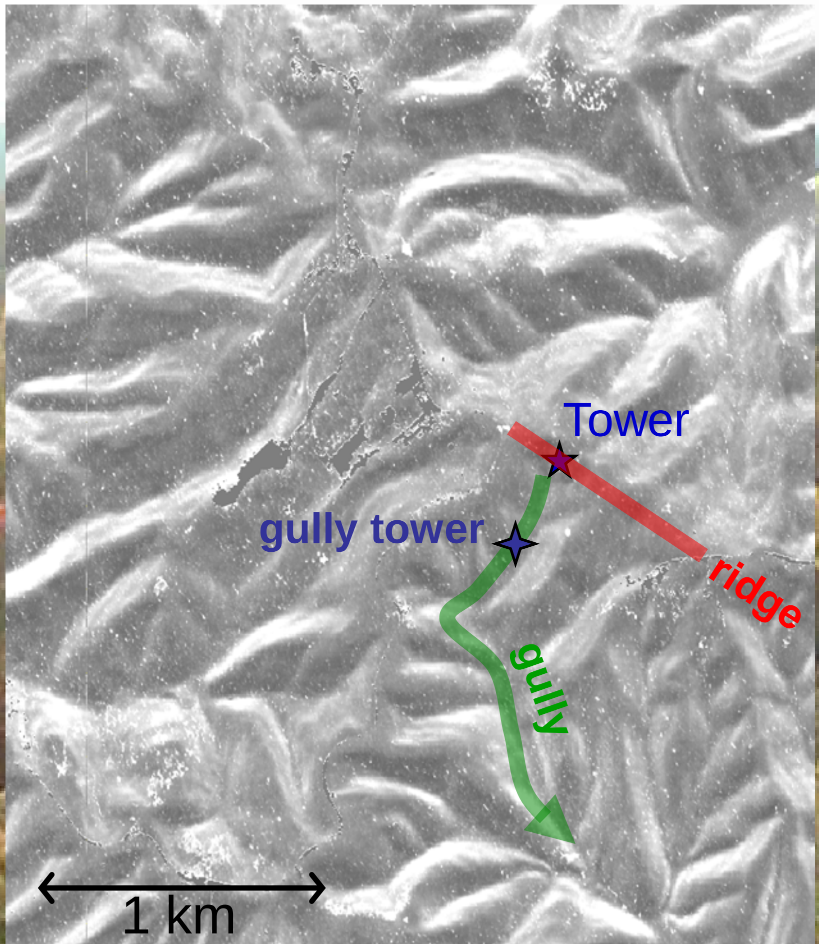
Aug 5 – Aug 13

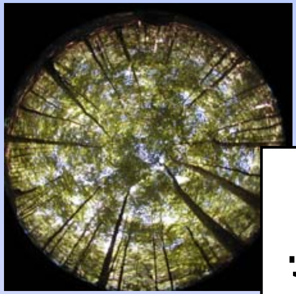
Problem with Nighttime Fluxes in Topography?

Is respired CO_2 at night "leaking" out of the box, without a trace detectable by the flux sensor?

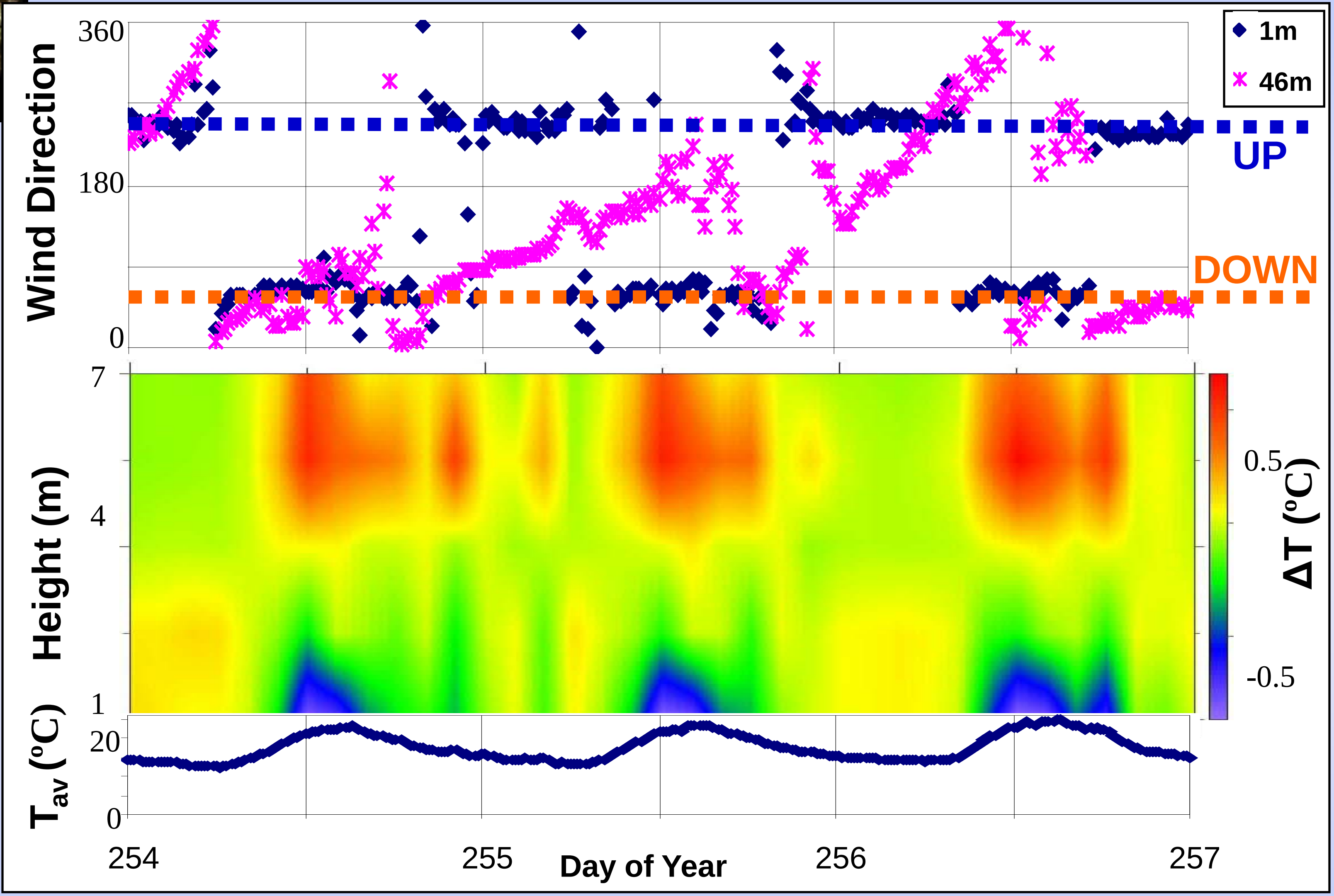
Advection and Gully Flows in Complex Forested Terrain



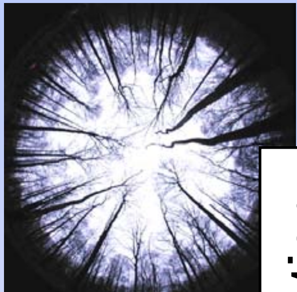




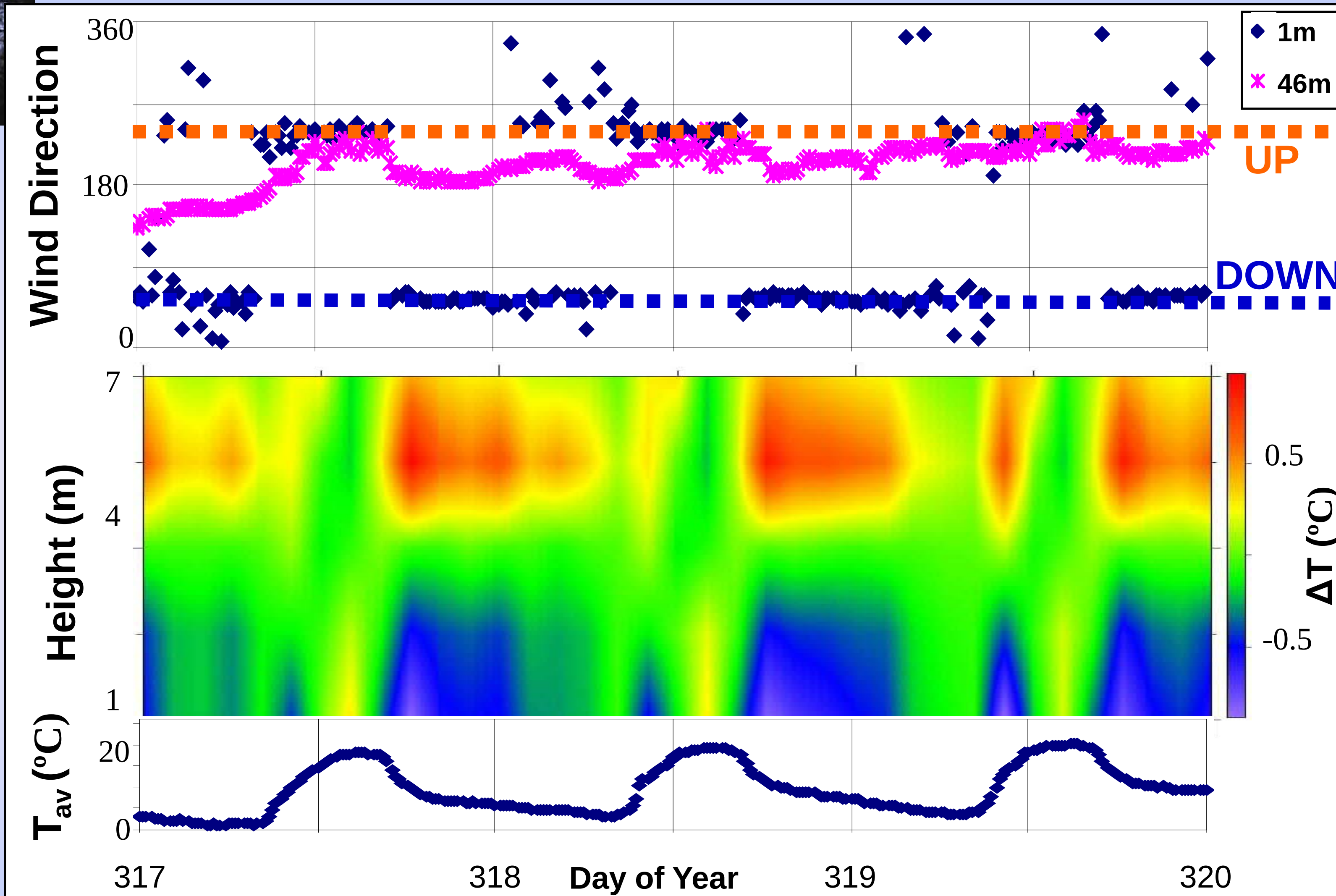
Thermotopographic Flow – Leaf-On



- Night «—» Up-gully flow with lapse conditions
- Day «—» Down-gully flow with inversion conditions

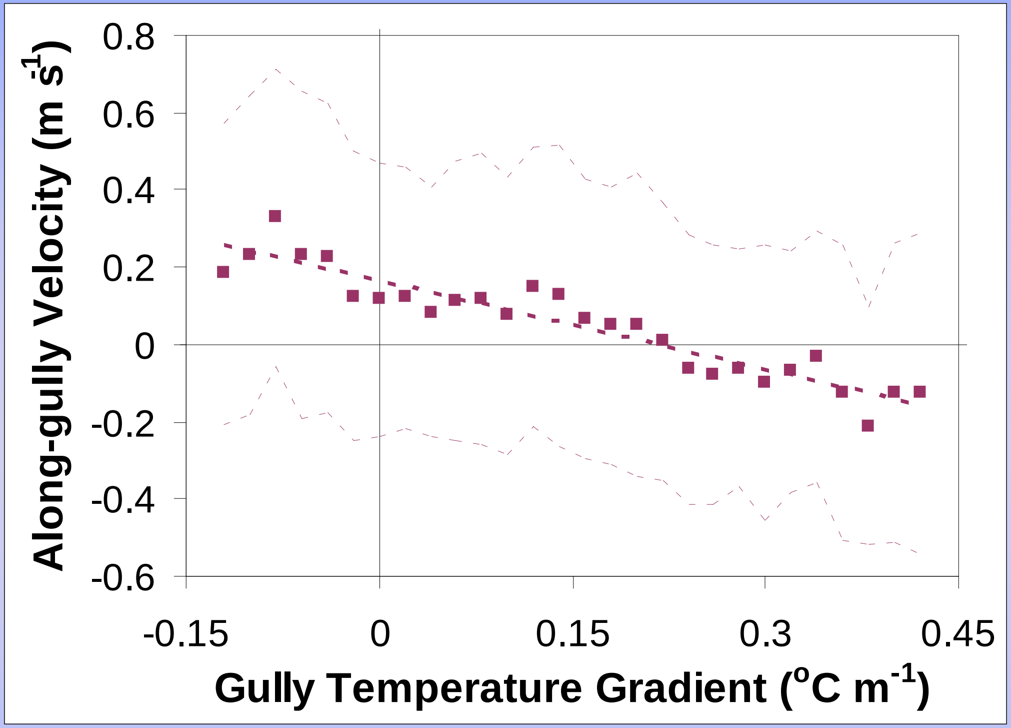


Thermotopographic Flow – Leaf-Off



- **Night «–» Down-gully flow with inversion conditions**
- **Day «–» Up-gully flow with lapse conditions**

Below-Canopy Temperature Gradient and Along-Gully Velocity



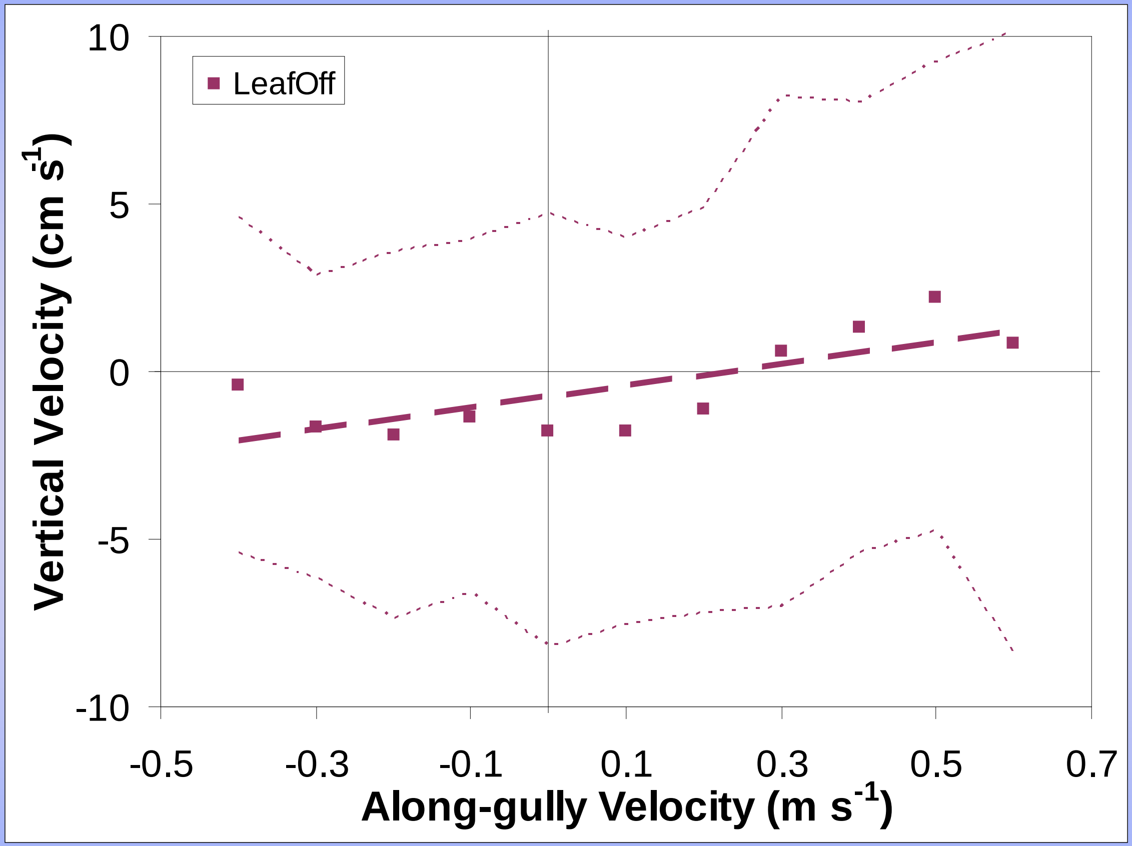
Includes all data bin-averaged data

temperature inversion «—» down-gully velocities

lapse conditions «—» up-gully velocities

Thermotopographic forcing of gully flows

Along-Gully Velocity and Vertical Velocity Above-canopy

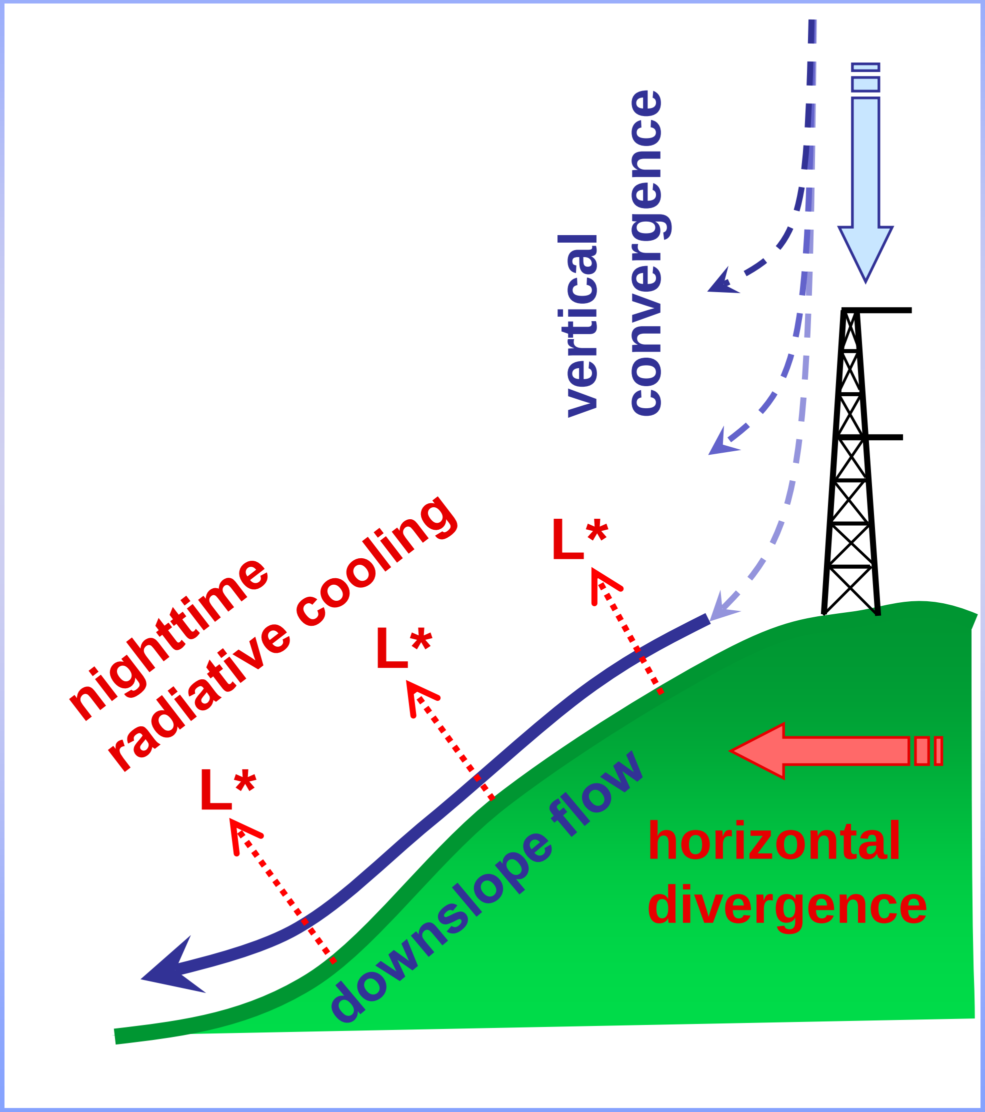


Includes all Leaf-Off data

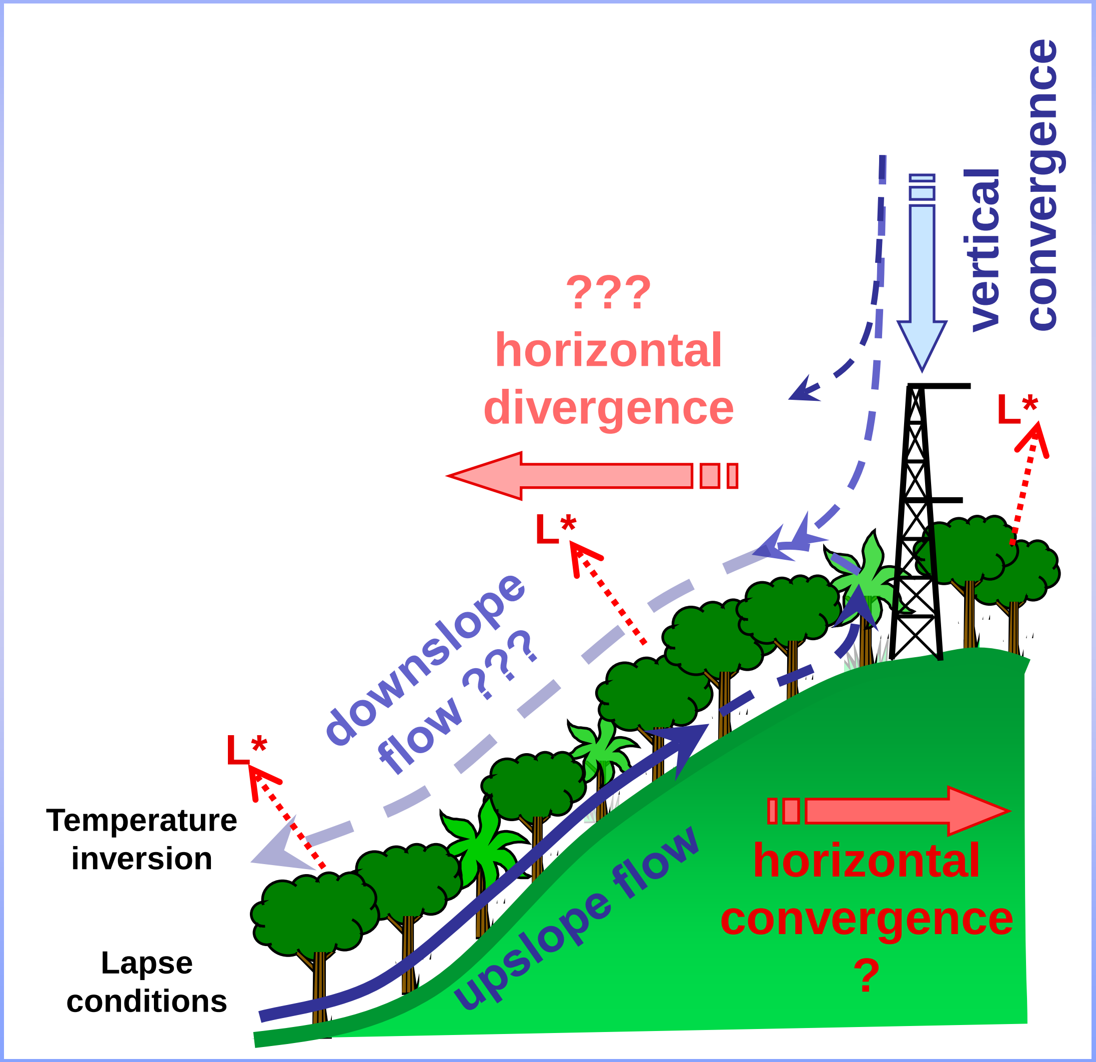
bin-averaged data

down-gully velocities «—» stronger convergence / weaker divergence aloft

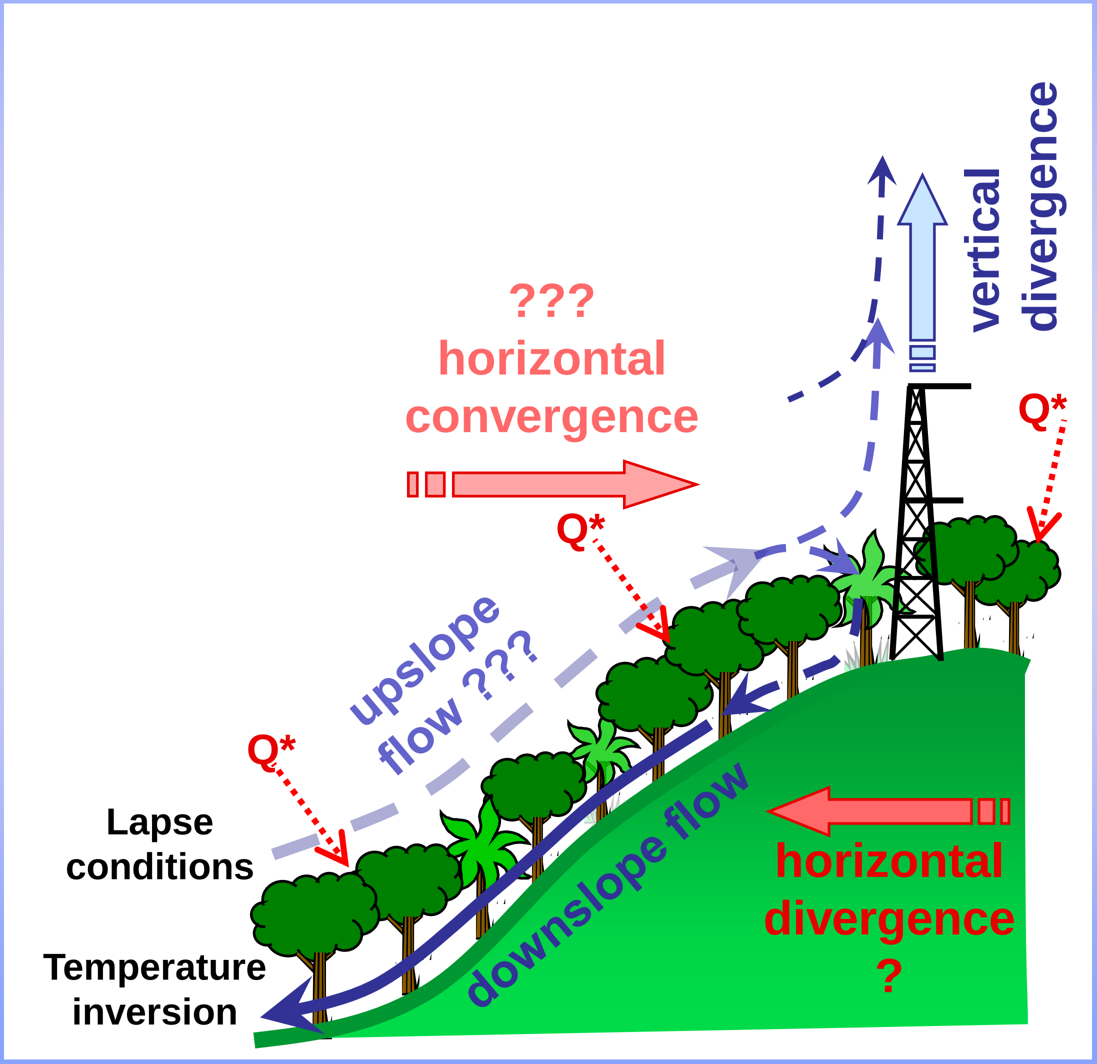
Flow Patterns: Leaf-Off Nighttime



Flow Patterns: Leaf-On Nighttime



Flow Patterns: Leaf-On Daytime



Summary of Results

Nocturnal vertical convergence above canopy

- **tendency to downward vertical velocities**

Nocturnal below-canopy thermotopographic flows

- **down-gully (divergence) in Leaf-Off season**
- **up-gully (convergence) in Leaf-On season**

Implications

Above-canopy conditions may misrepresent below-canopy conditions

Need to consider complex 3-D flow patterns at each site, via both measurement campaigns and modeling

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MMSF

UMBS

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