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
- 1-D gradients

Haugen *et al.* 1971 (QJRMS, 97, 168-180)

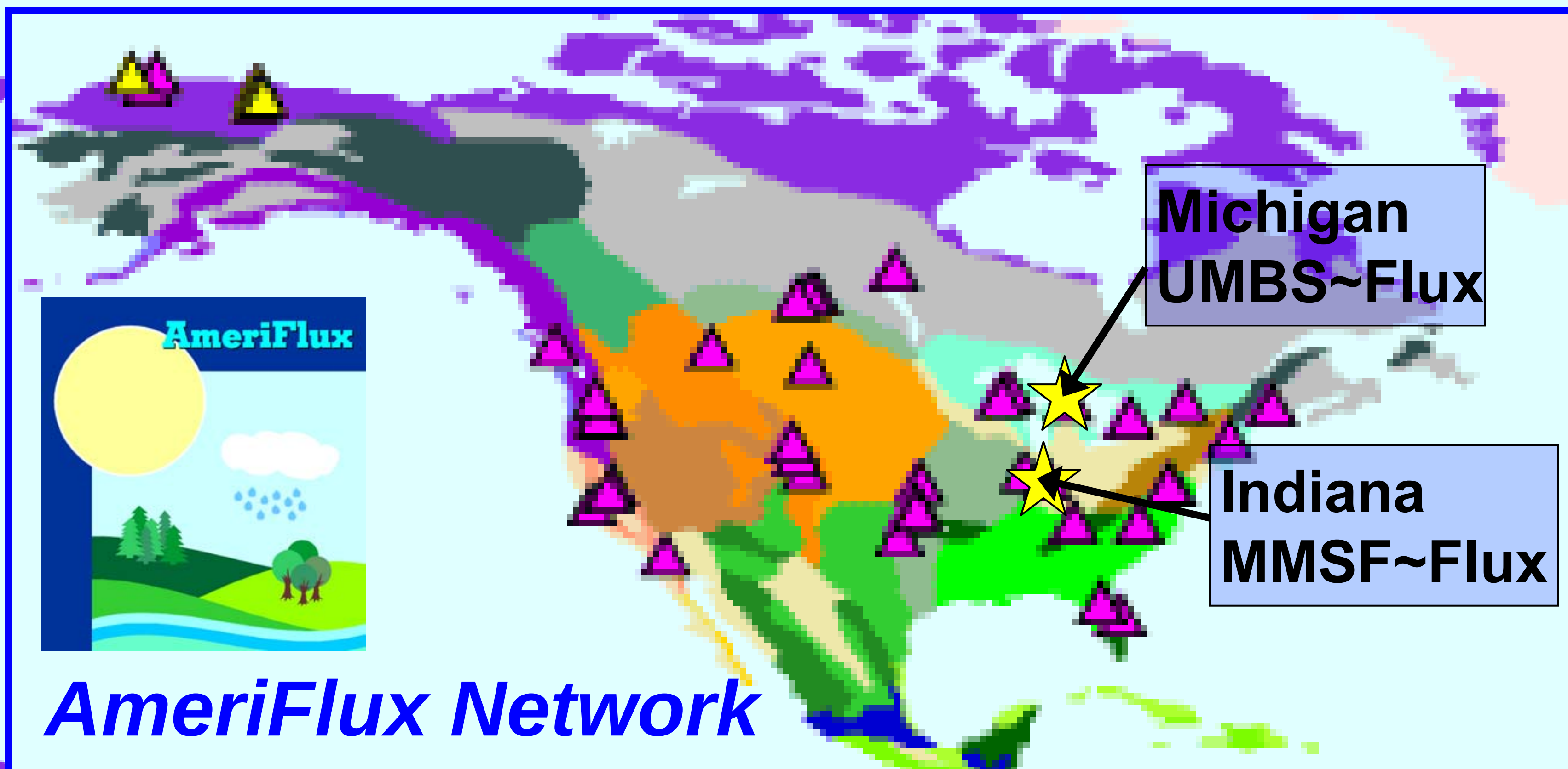
MMSF & UMBS
1998-2001

- tall forest (23-28 m)
- ridge-ravine terrain; gentle slope
- ~ 40‘000 hours data (2+2 levels)
- tower: 47 m
- z/h < 2.1
- 3-D „mess“

Why deviate from ideal sites?

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:

• 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

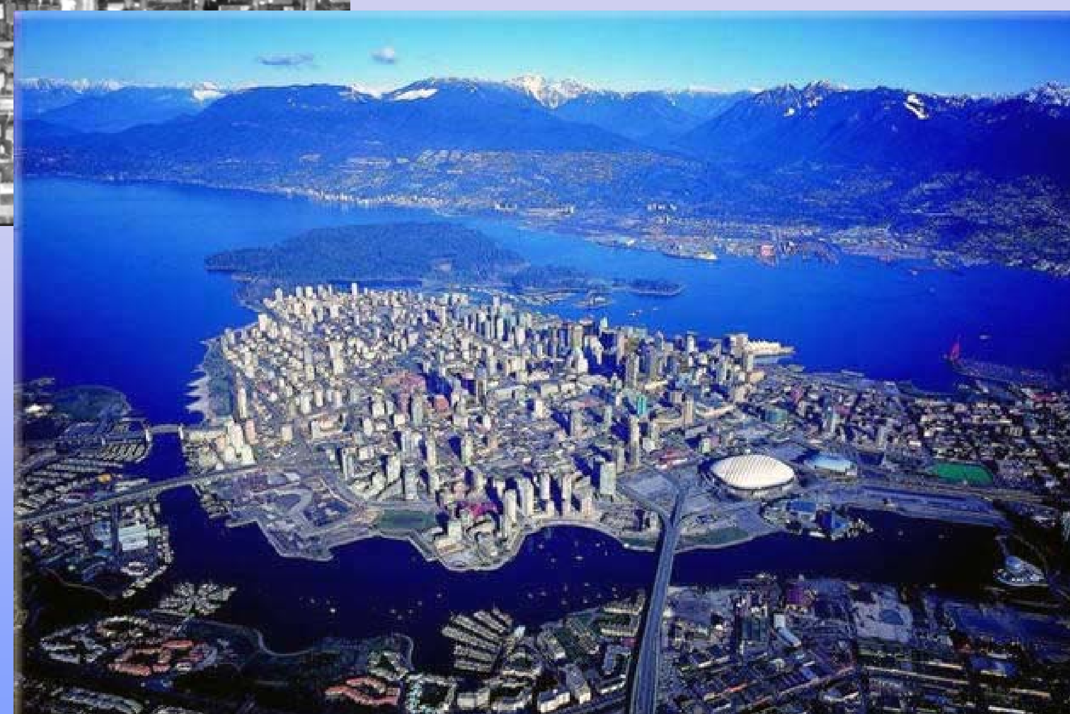
Large Scale Topography

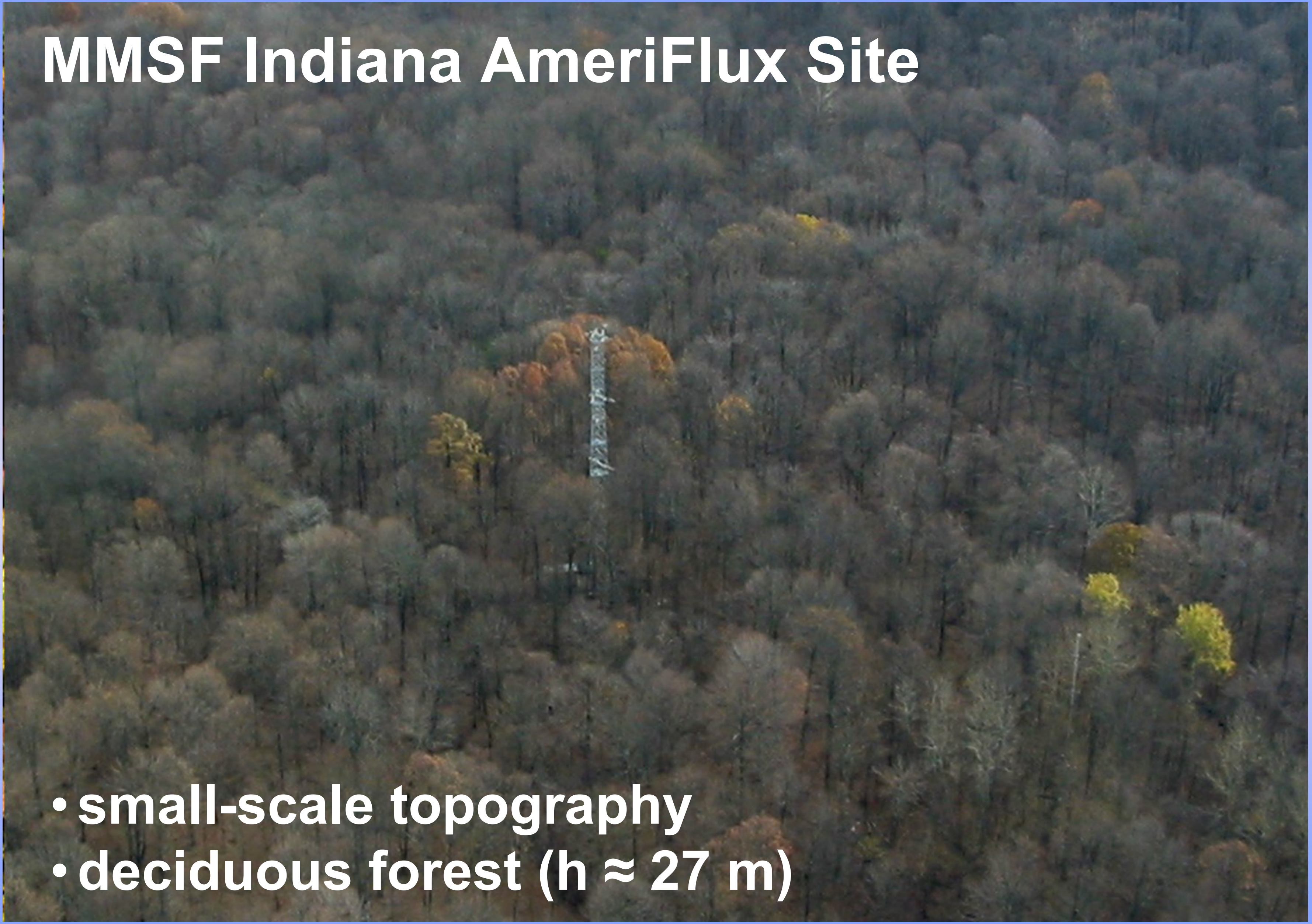
Small Scale, Gentle Topography

Difficult Conditions: Urban

Large Rigid Obstacles, Patchiness

All Effects, All Scales




MMSF Indiana AmeriFlux Site
• small-scale topography
• deciduous forest (h ≈ 27 m)

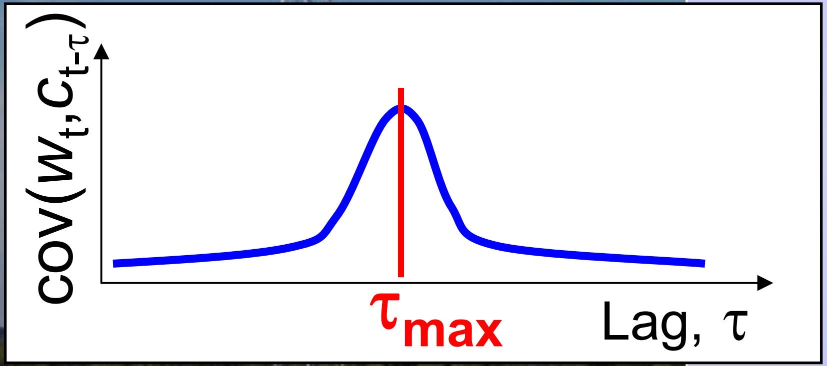
Eddy-Covariance: Closed Path System

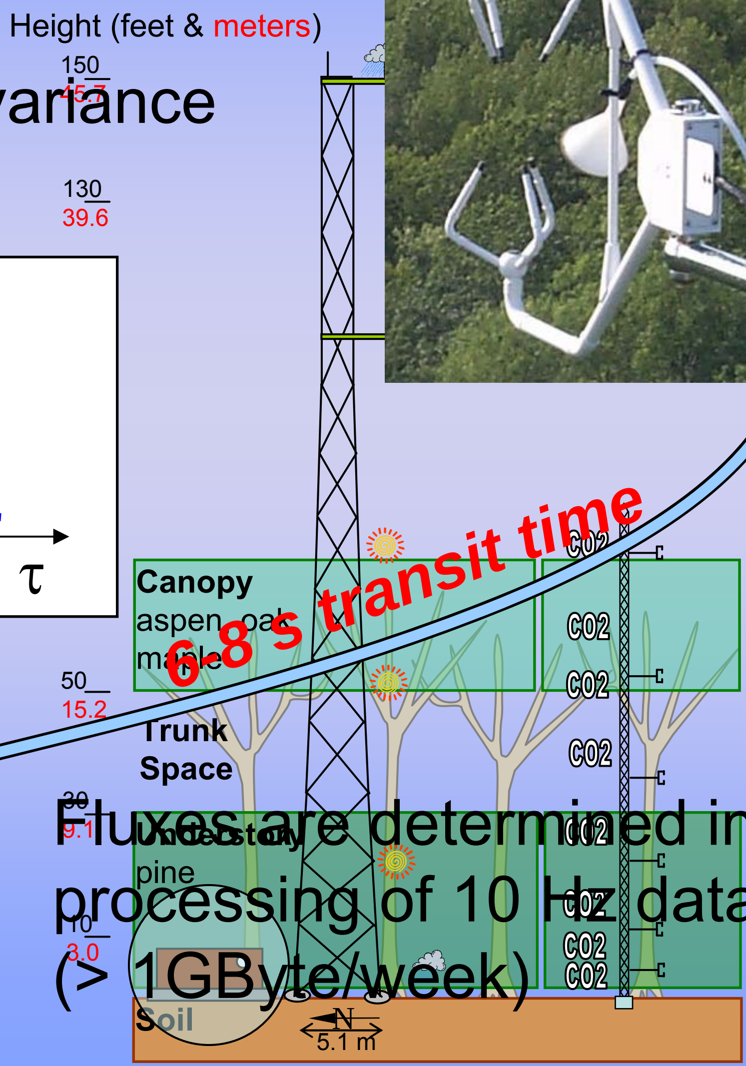
UMBS~Flux Tower: Instrumentation

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

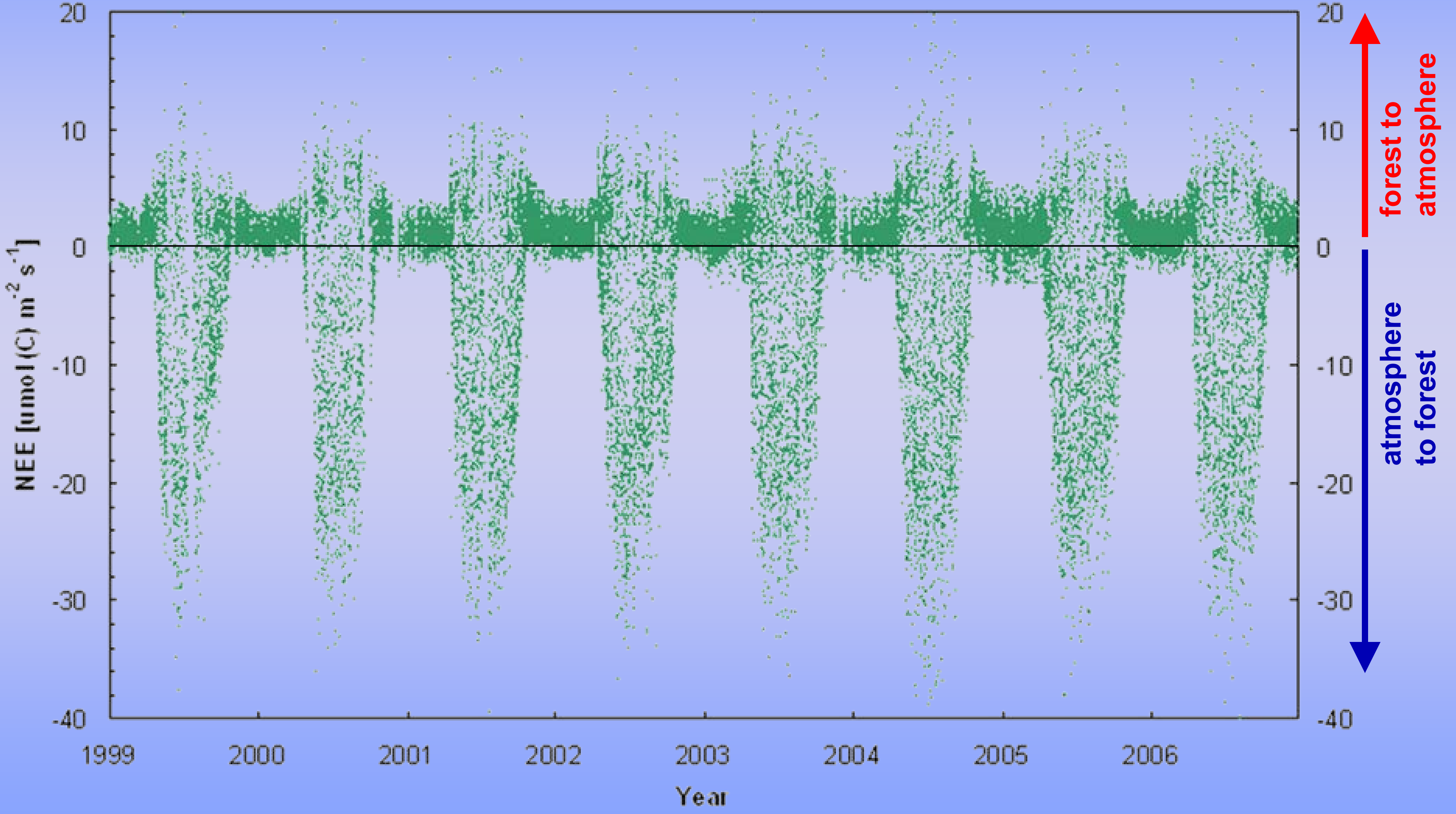




Fluxes are determined in post-processing of 10 Hz data-stream (> 1GByte/week)

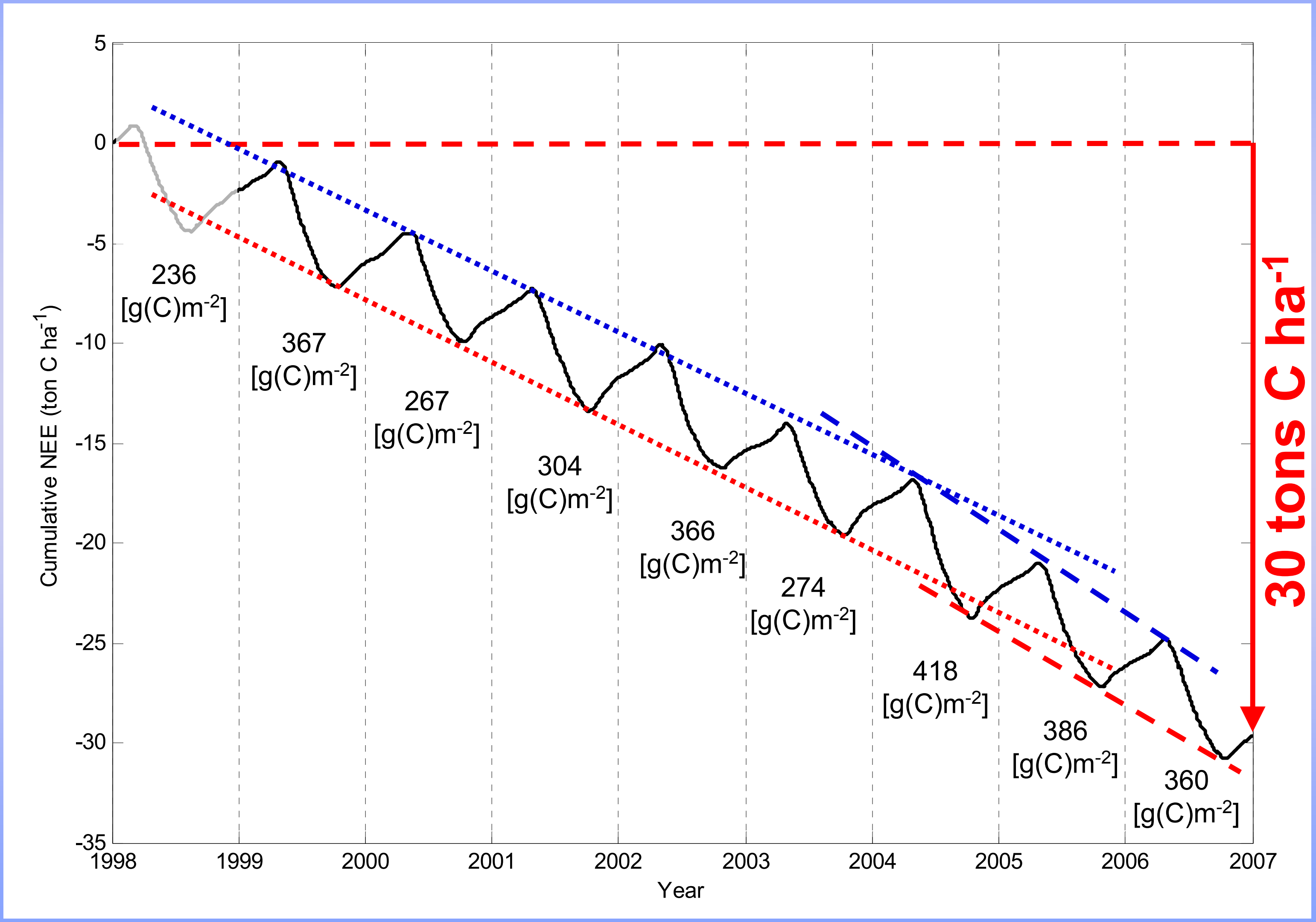
Hourly Fluxes of CO_2 over 8 Years (MMSF)

NEE: *Net Ecosystem Exchange* = Respiration - Assimilation



Cumulative Exchange of CO_2 over 9 Years (MMSF)

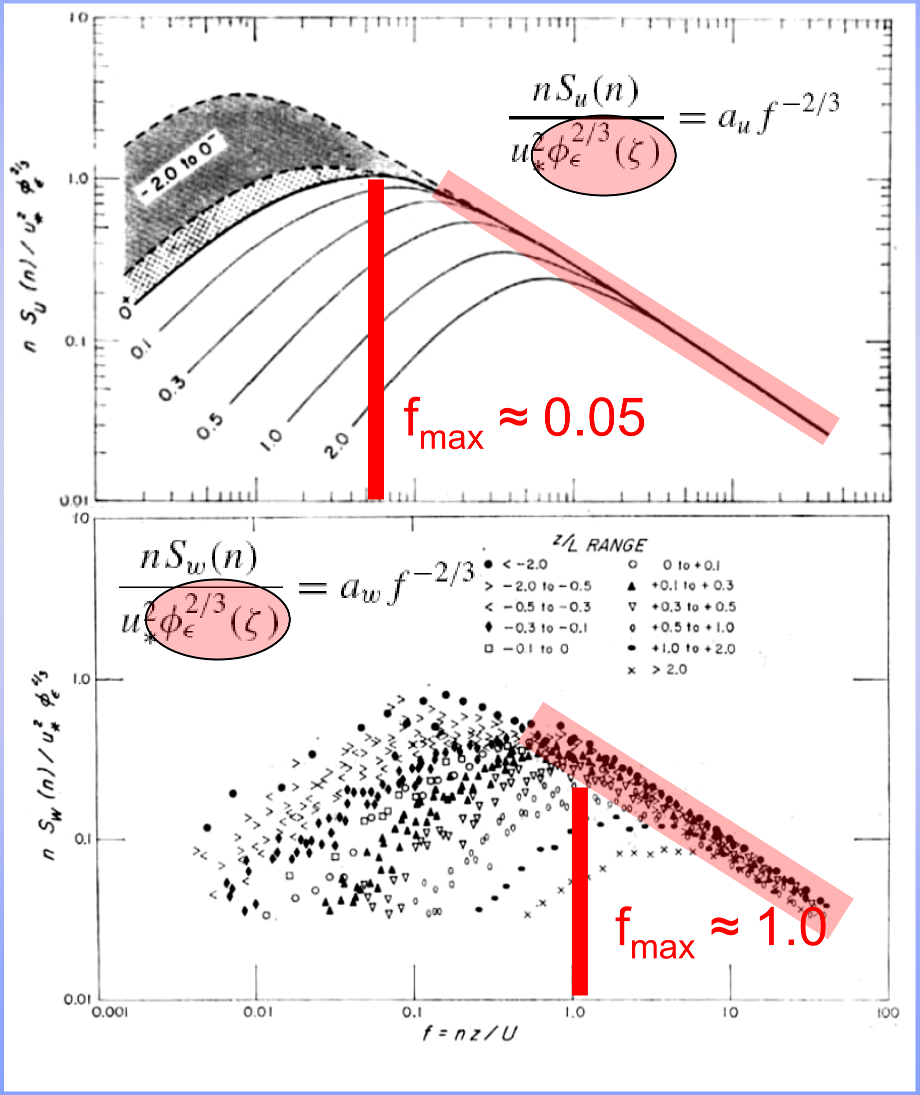
NEE: *Net Ecosystem Exchange* = Respiration - Assimilation



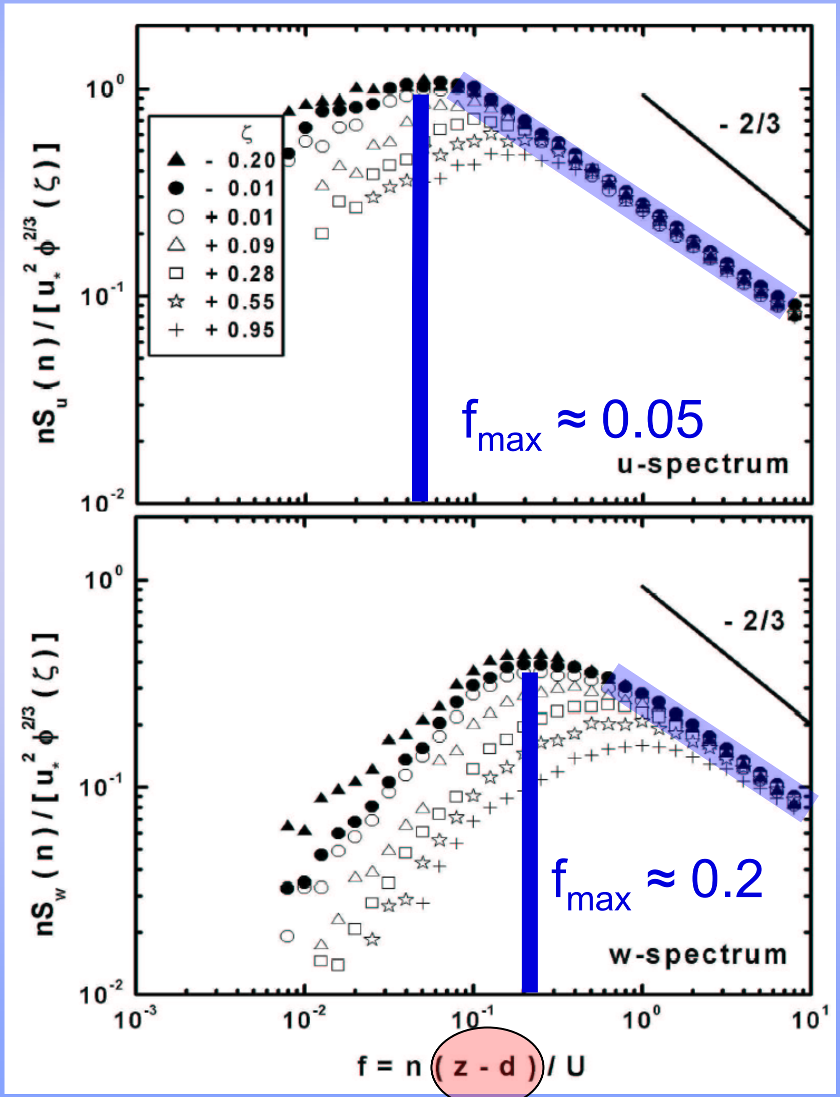
30 tons C ha^{-1} = 3 kg C m^{-2}

Turbulence Characteristics: how far from Kansas are we?

Kansas



UMBS, 46 m, foliated

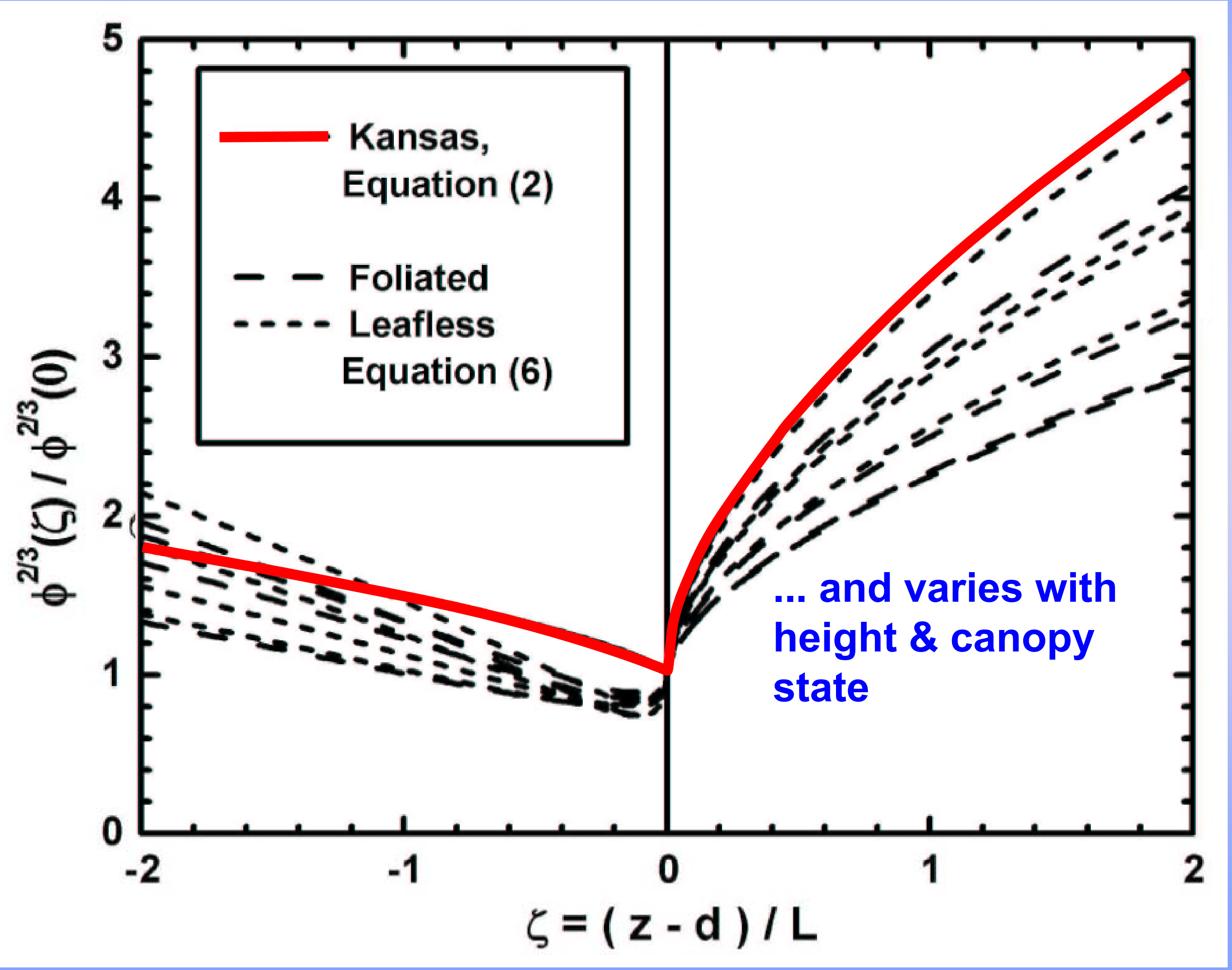


Kaimal *et al. 1972 (QJRMS* **98,** 563–589)

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

Turbulence Characteristics: not so far from Kansas ...

... but non-dimensional TKE dissipation rate [Φ(ζ)] is different over tall canopy

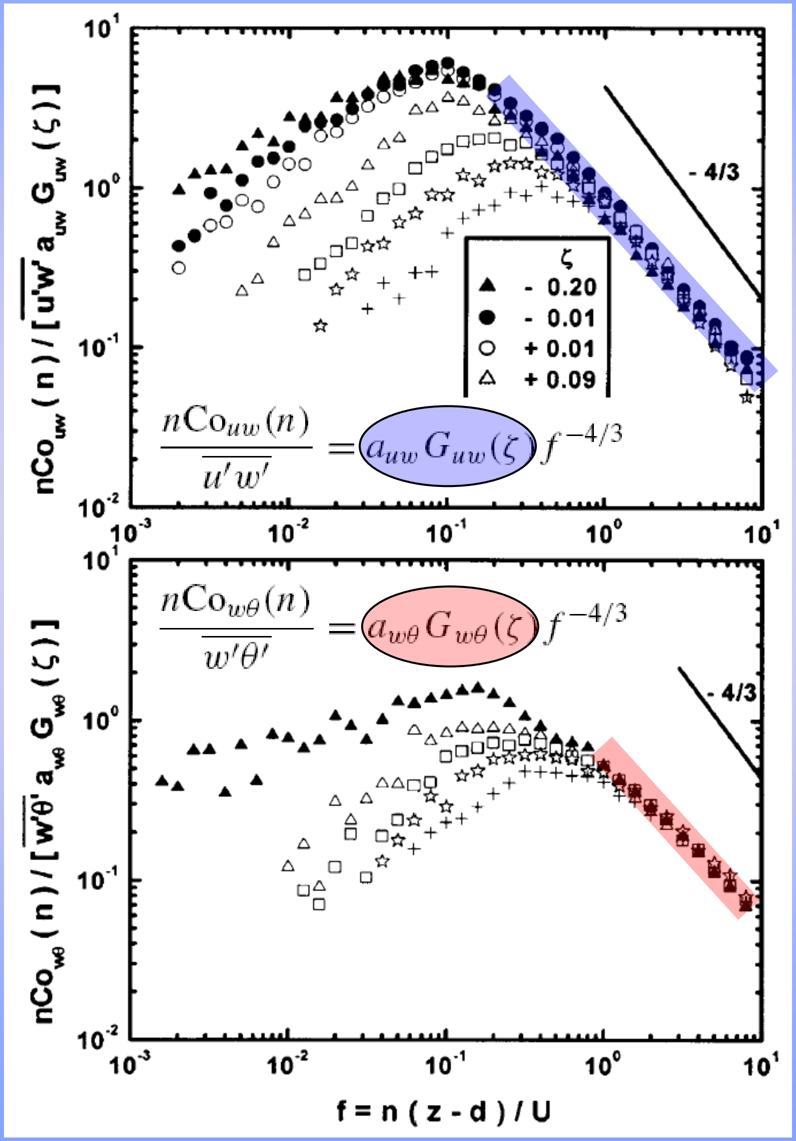


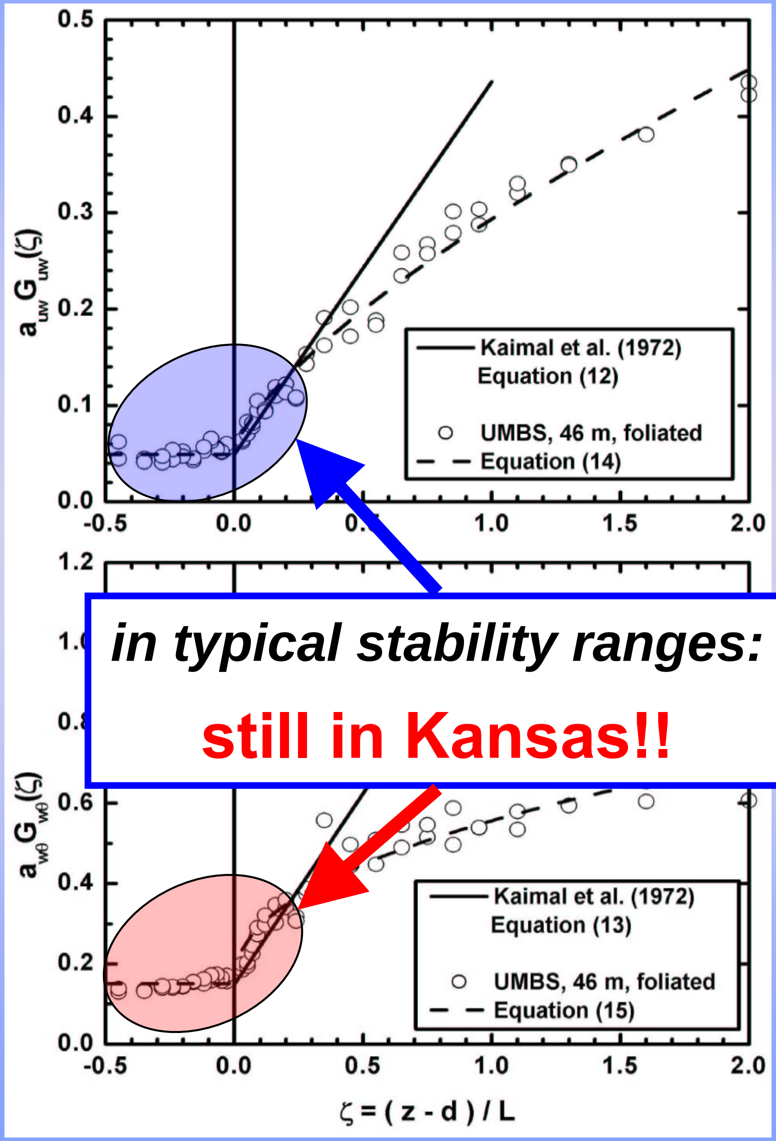
... and varies with height & canopy state

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

Turbulence Characteristics: uw & wθ Co-Spectra

... non-dimensional flux dissipation rates [G(ζ)] are different over tall canopy





in typical stability ranges:

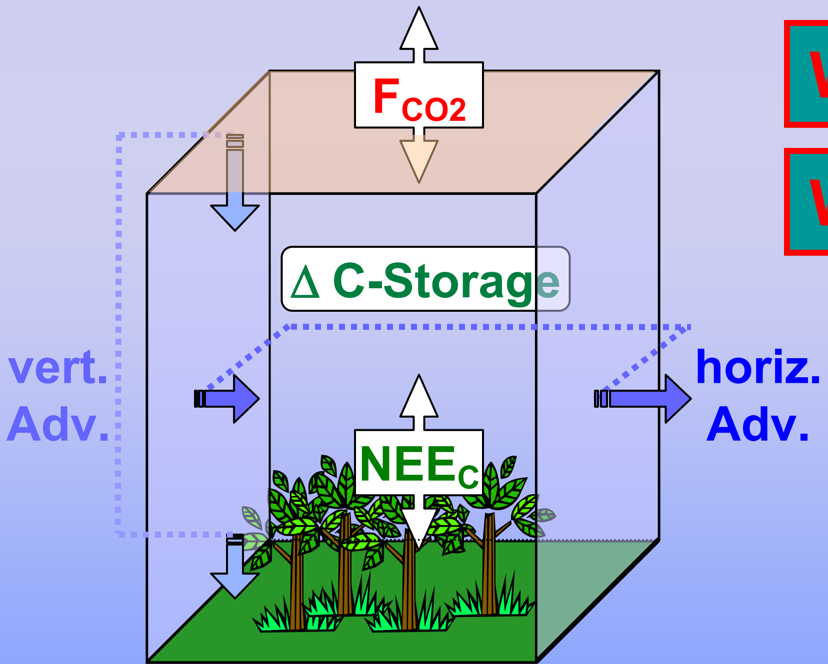
still in Kansas!!

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

Are fluxes capturing the right processes ?

Examine CO_2 Conservation Equation!

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



What do we want? **NEE !**

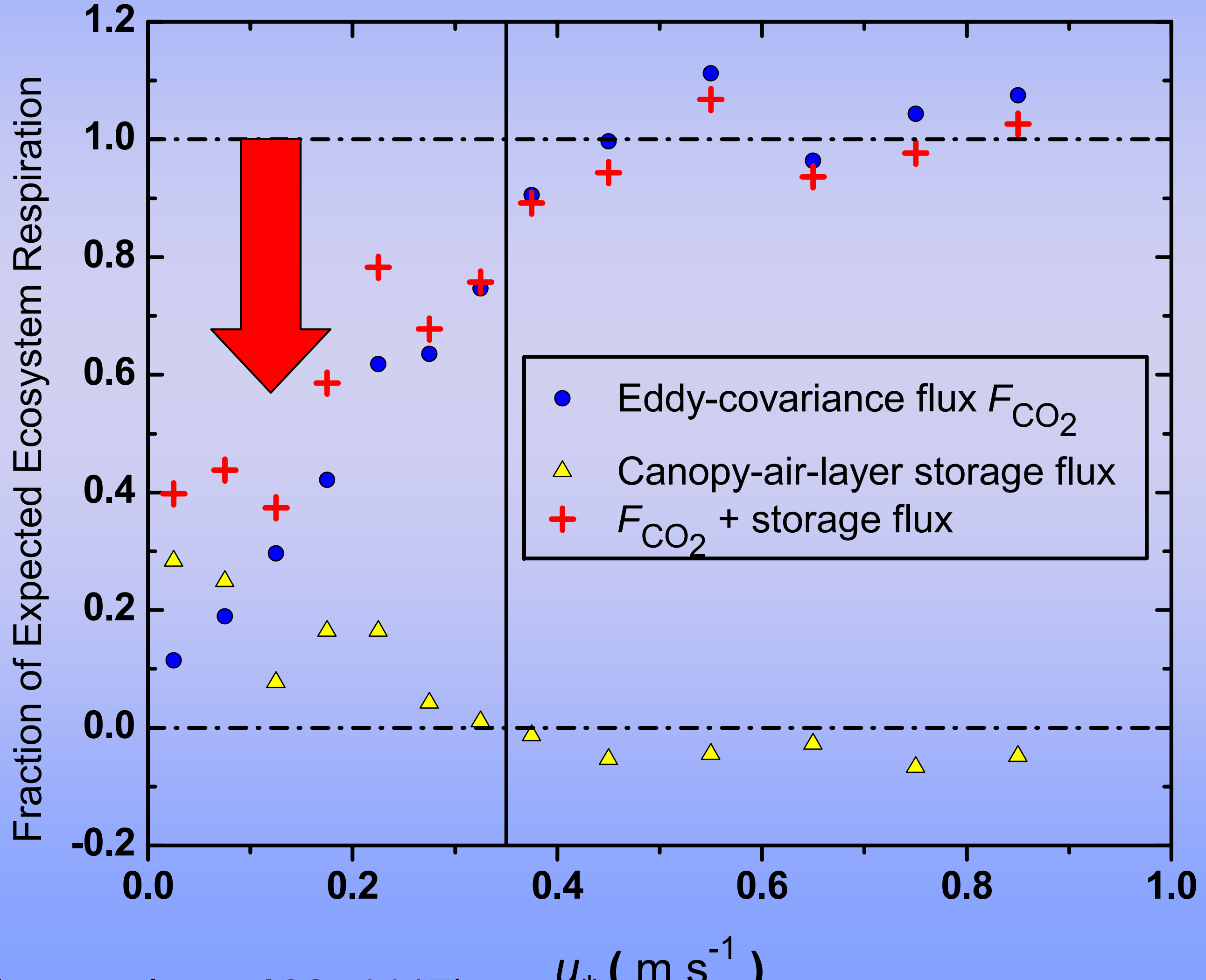
What do we have? **F_C (+ storage)!**

Potential problems:

- location, shape of the box
- "leaking" out of the box

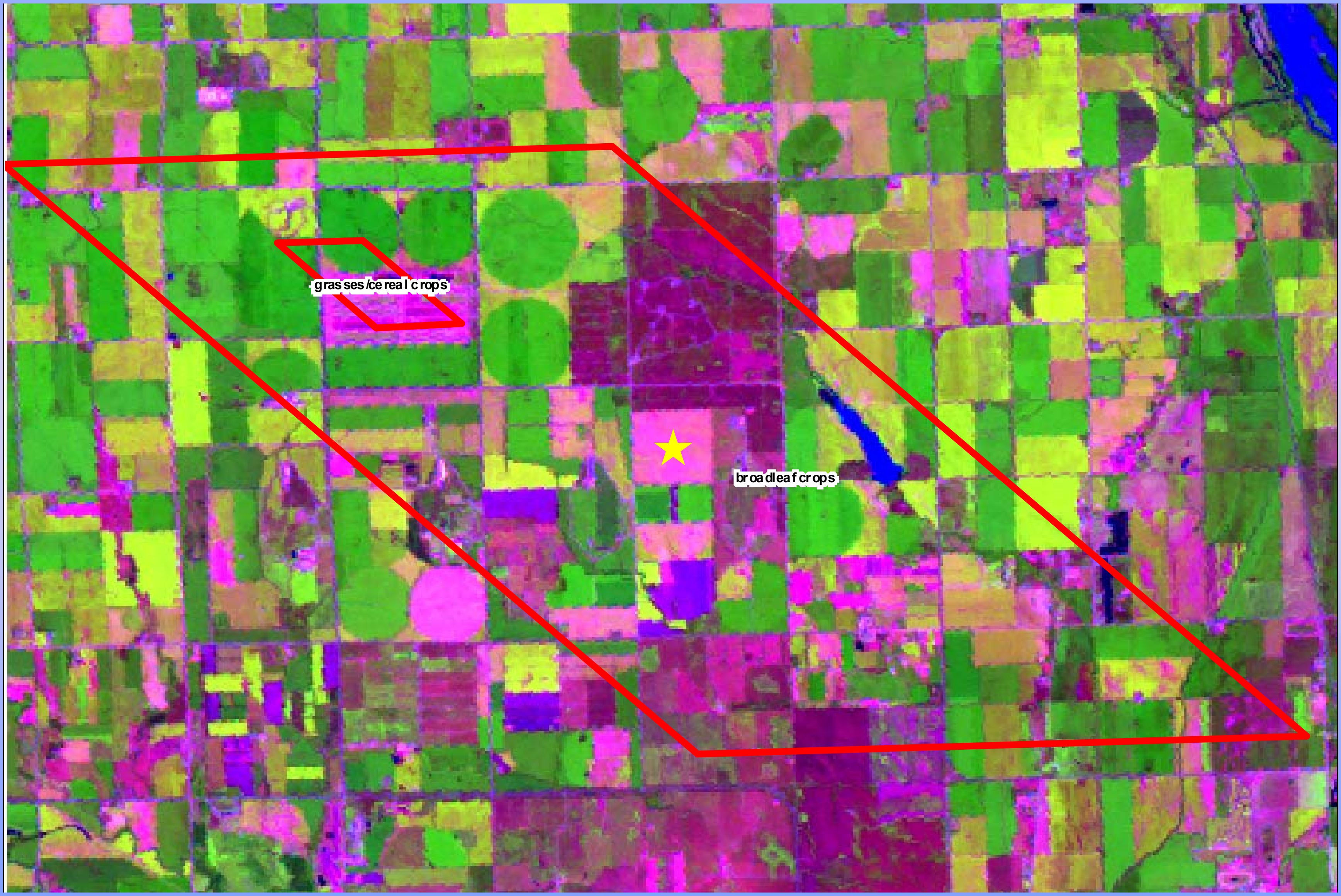
Eddy Flux and Storage Term

- lack of closure indicates **advection** important at low u* values
- advection indicates **horizontal inhomogeneity** of sources/sinks

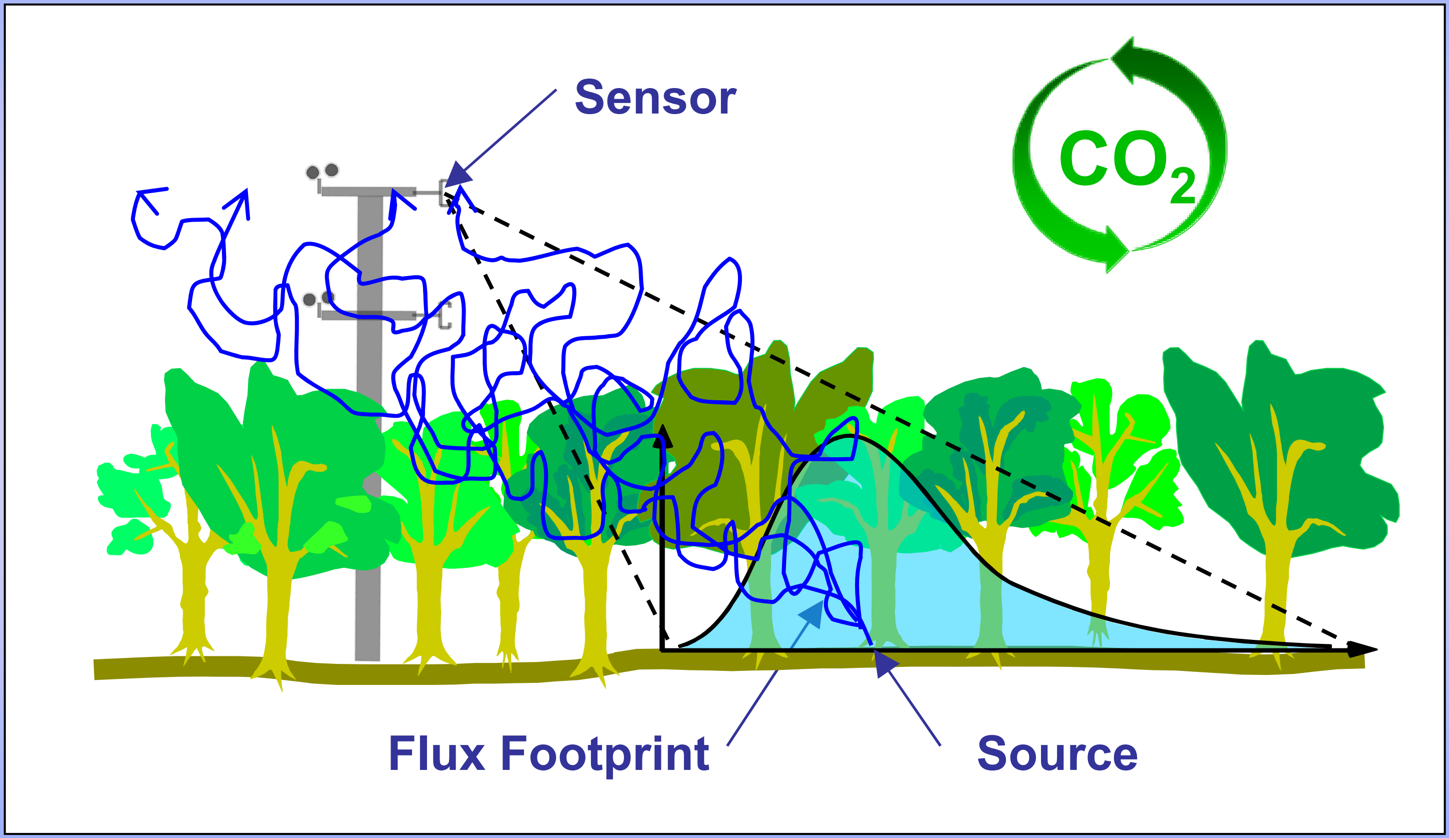


Schmid *et al. 2003* (*JGR* **108,** 4417)

Mead rain-fed: land use



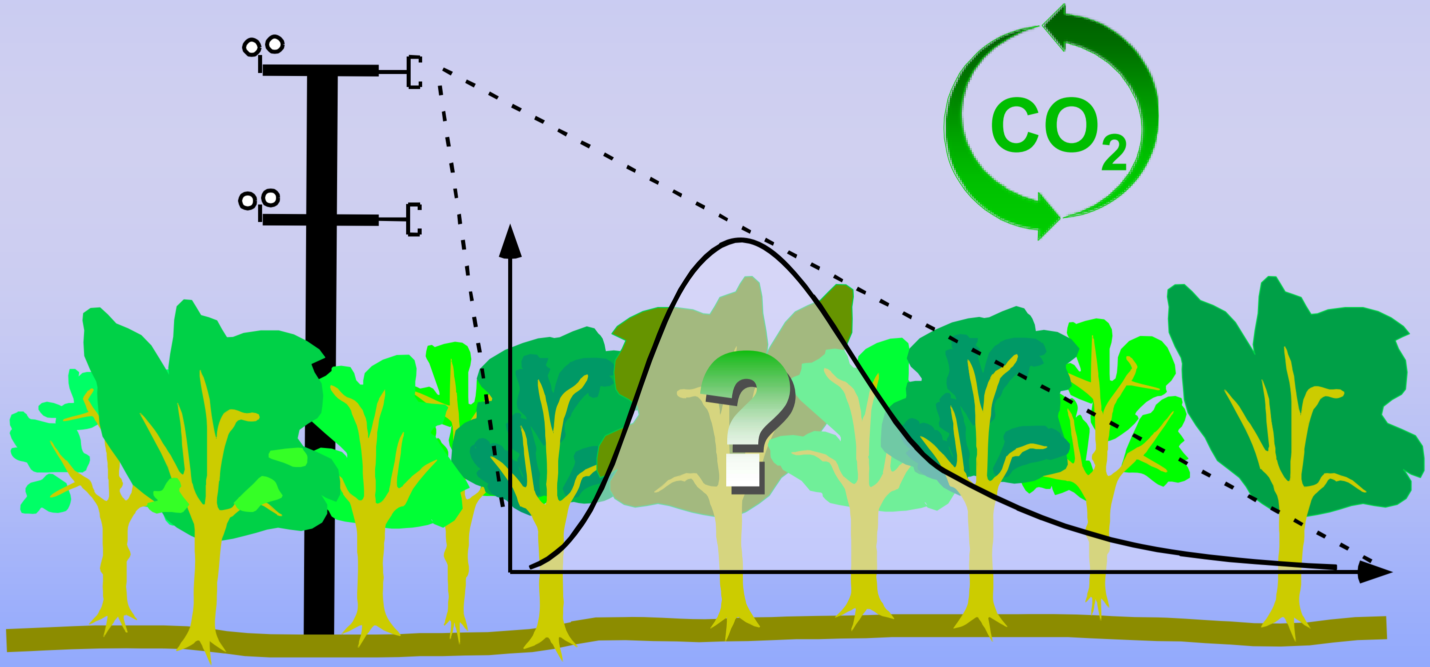
Micrometeorological Flux Measurements:
at what scale?



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

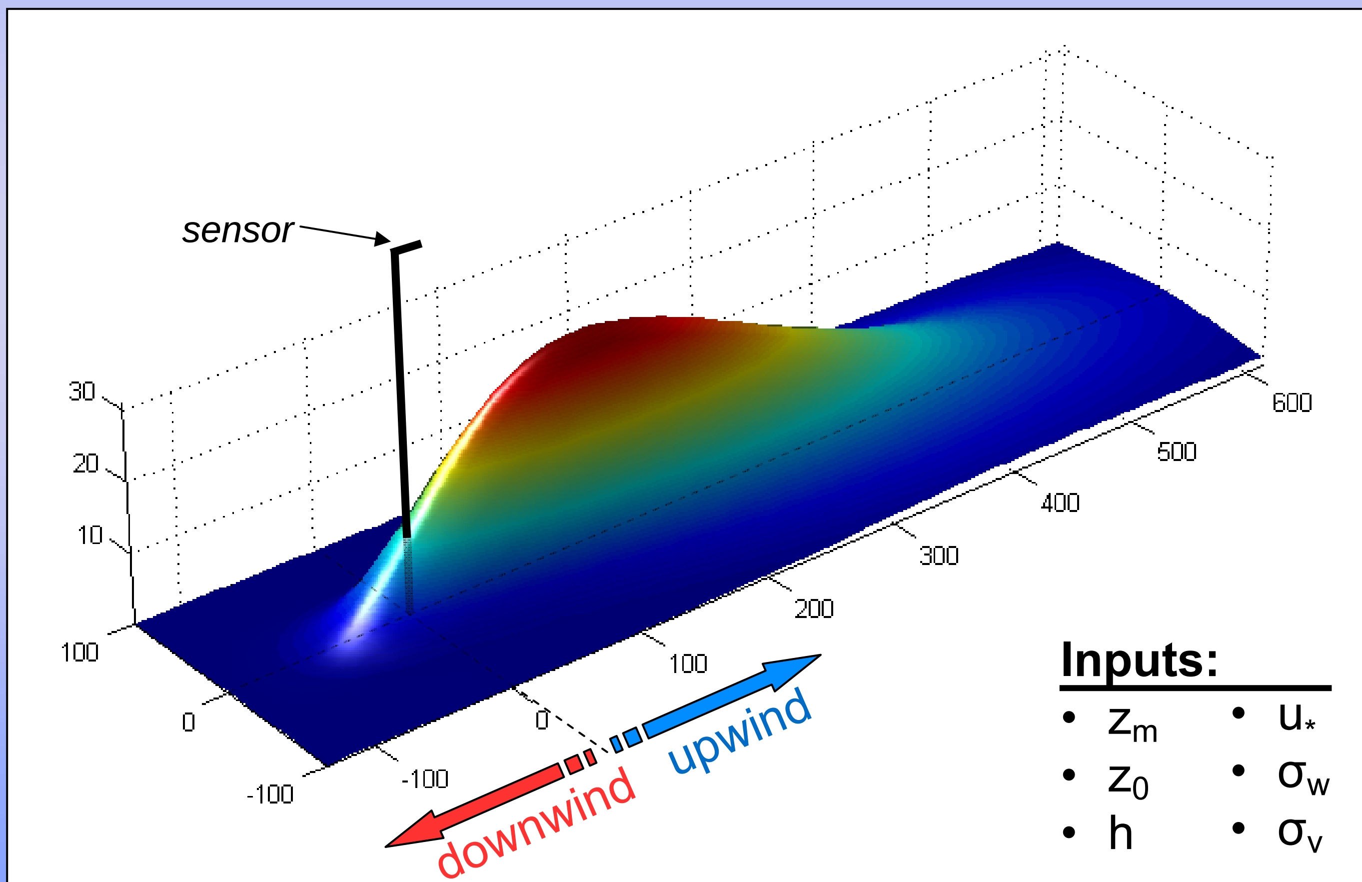


e.g.: Schmid (2002, *Ag. For. Met.*, **113**, 159-184)

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**, $\boldsymbol{Q_s}$, with the **footprint**, $\boldsymbol{f}$)



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

Concentration and Flux Footprint Models

Governing equations in Eulerian analysis:*

advection **diffusion** **forcing**

$$\bar{c}: \quad \bar{\mathbf{u}} \cdot \nabla \bar{c} + \nabla \cdot \left[K_F \frac{\partial \bar{c}}{\partial z} \right] = Q_S(\mathbf{x})$$

← **surface sources**

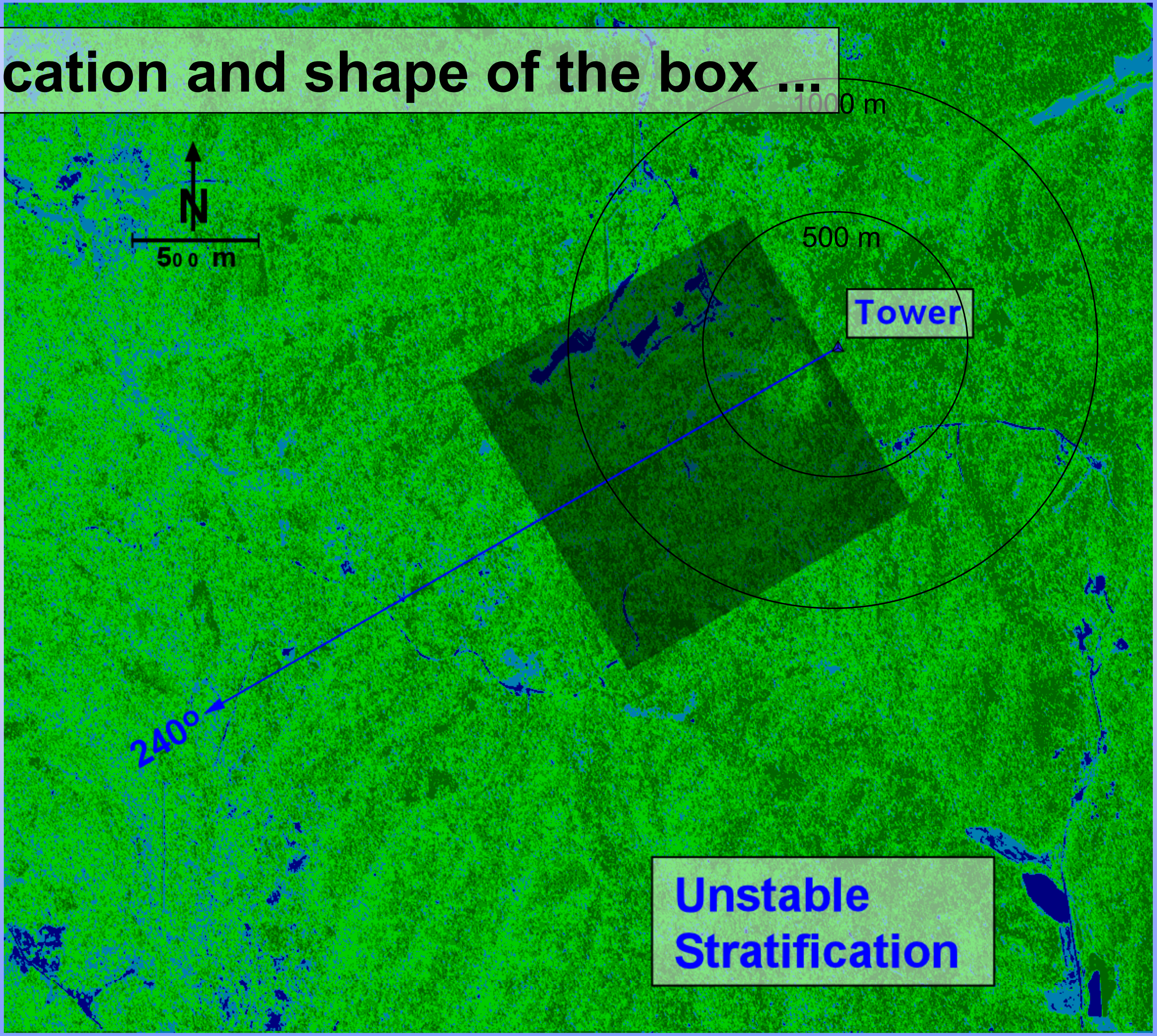
$$F: \quad \bar{\mathbf{u}} \cdot \nabla F + \nabla \cdot \left[K_F \frac{\partial F}{\partial z} \right] = -\overline{\mathbf{u}'^2} \cdot \nabla \bar{c}$$

← **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

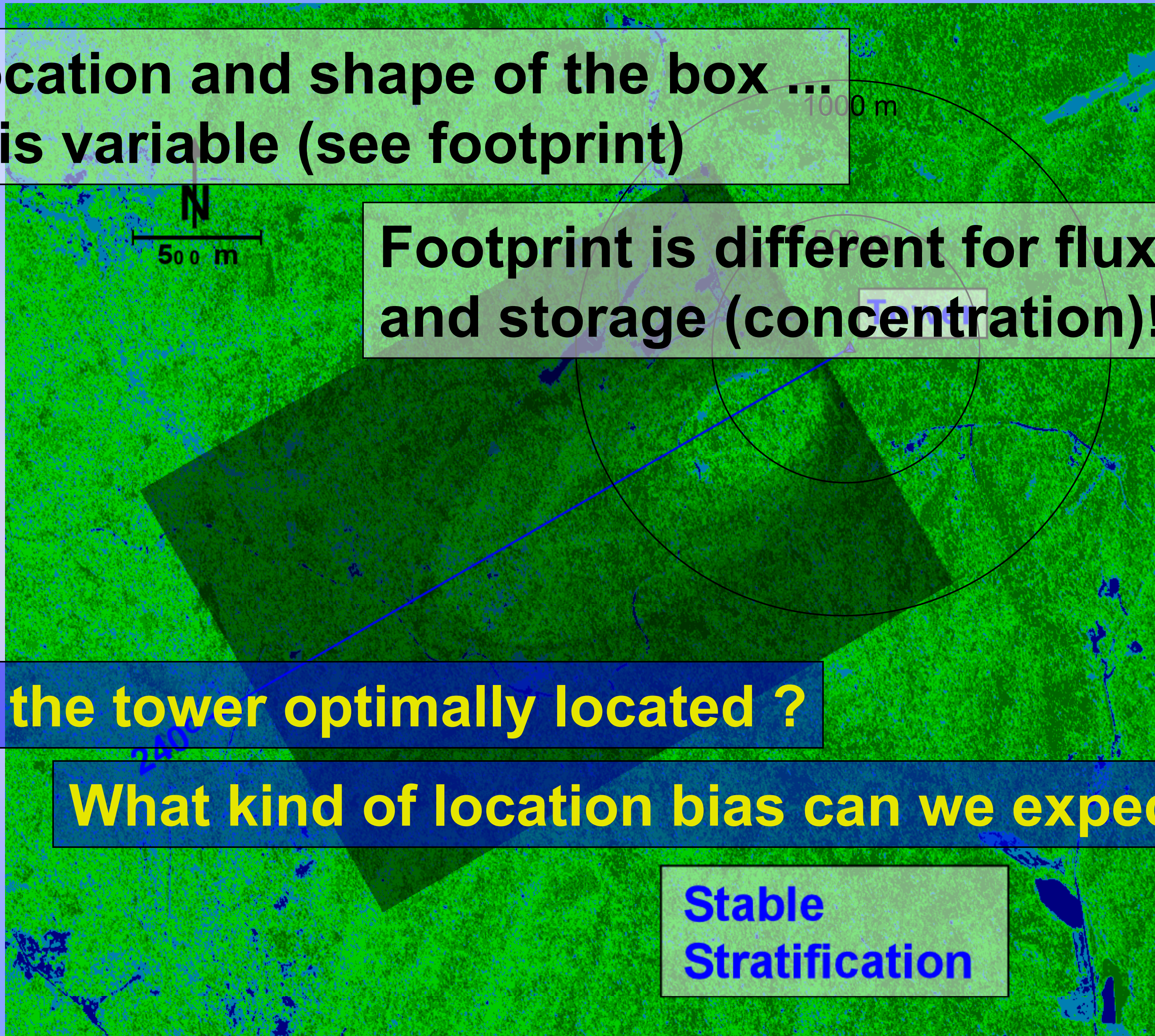
* following Finnigan (2004, AgForMet 127, 117-129); neglecting horizontal turbulent fluxes and pressure interactions.

Location and shape of the box ...



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

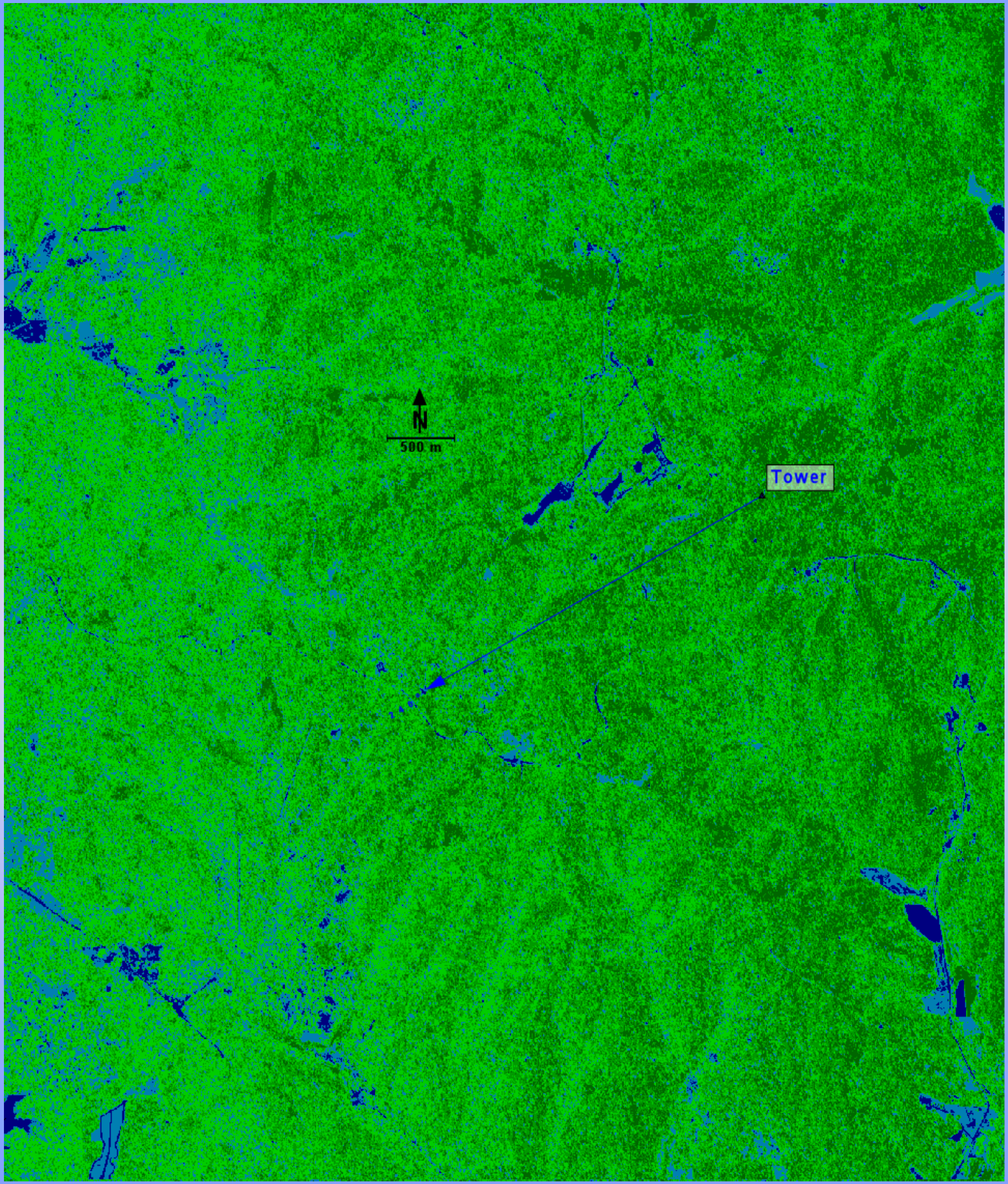
Footprint is different for flux and storage (concentration)!



Is the tower optimally located ?

What kind of location bias can we expect ?

Stable Stratification



- **Original NDVI:**

NDVI Variance: 0.053 (= 100 %)

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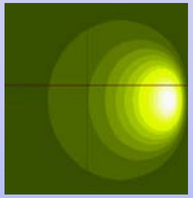
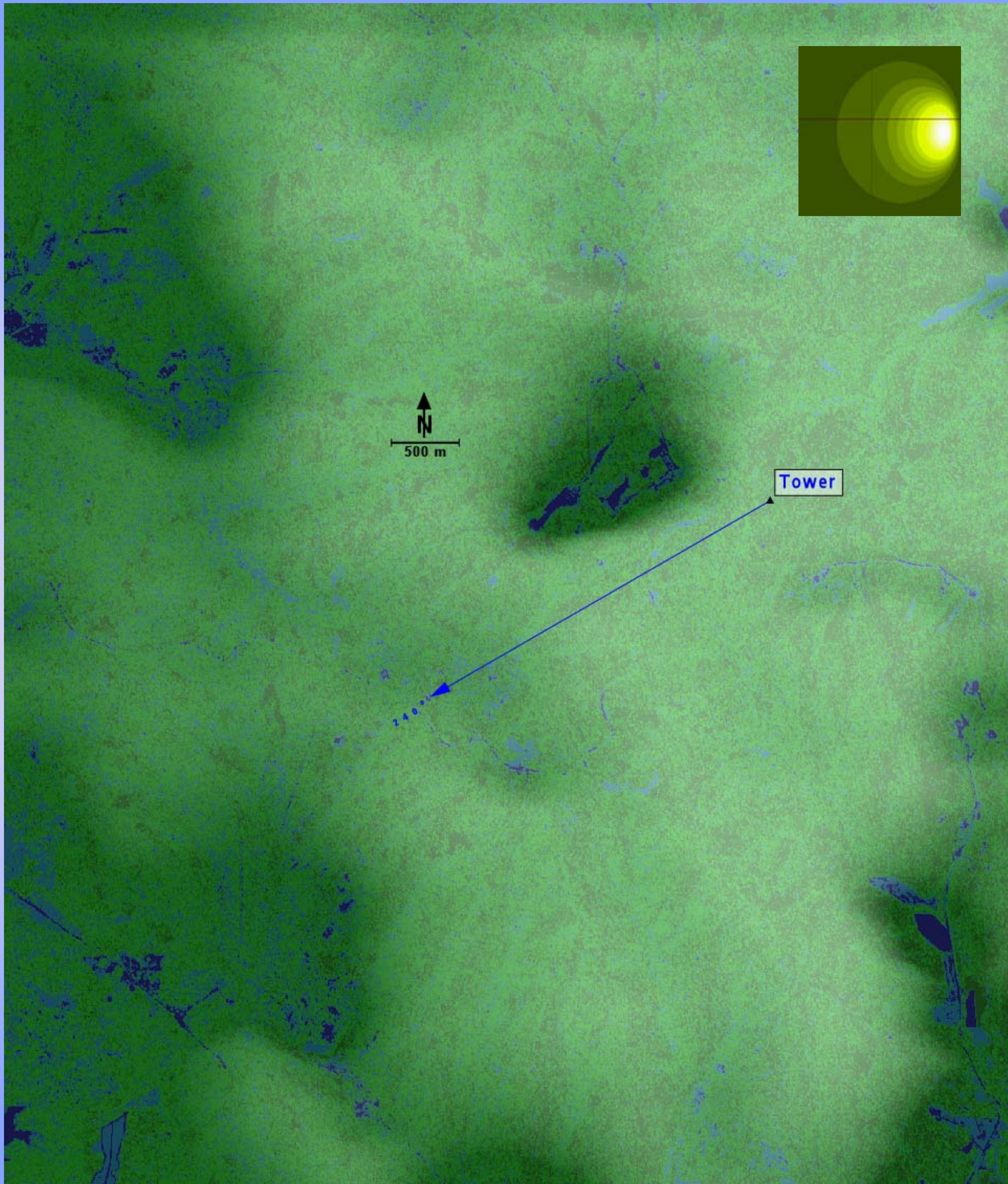
NDVI Variance: 0.053 (= 100 %)

- **Filtered NDVI:**

Unstable FSAM filter
Remaining Variance: 28 %

FSAM Filter Size:





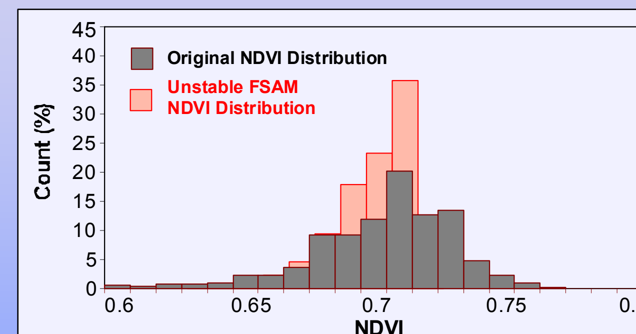
- **Original NDVI:**

  NDVI Variance: 0.053
  (= 100 %)

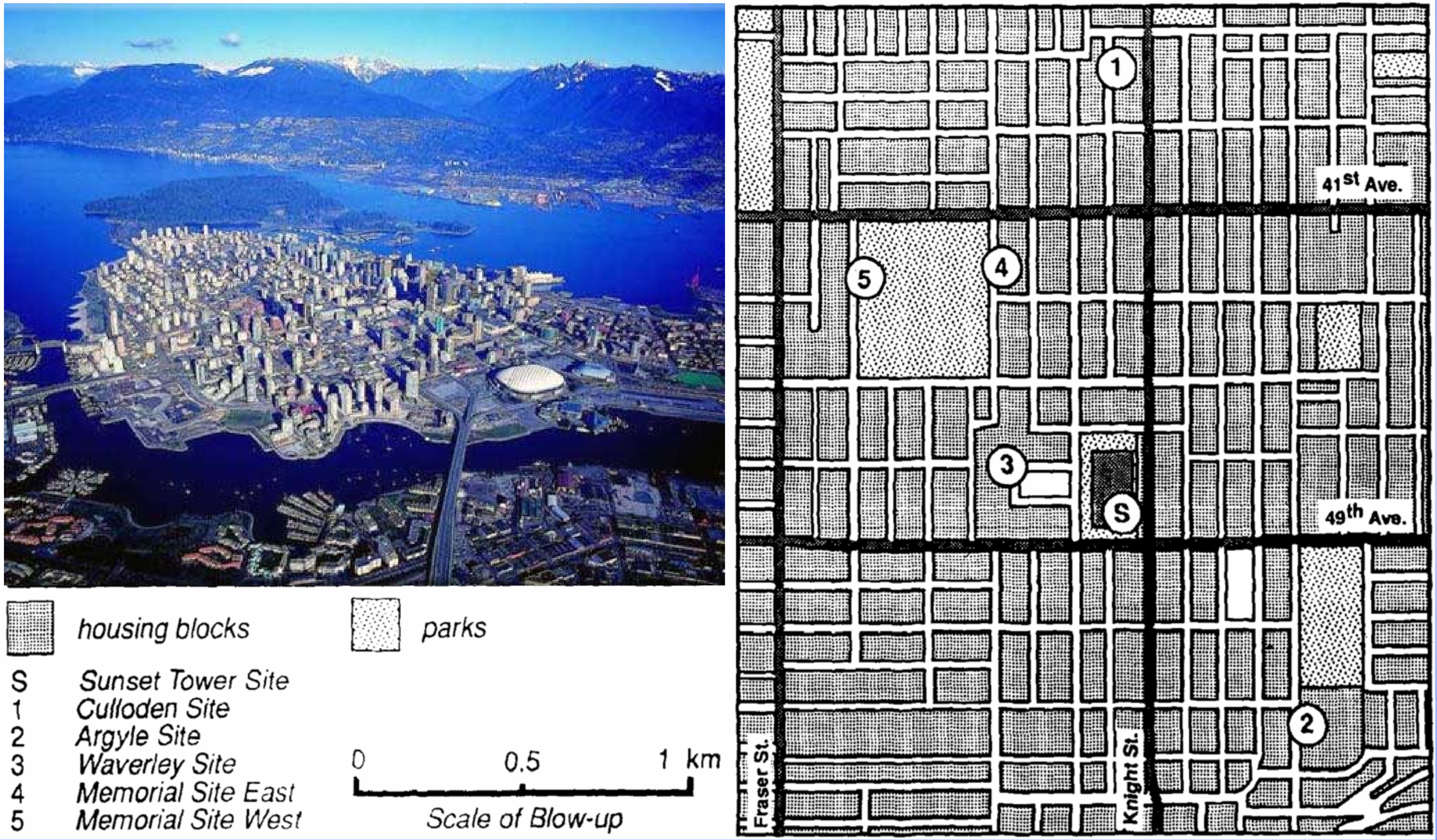
- **Filtered NDVI:**

  Unstable FSAM filter
  Remaining Variance:
  28 %

- Histogram Comparison:



... short excursion to urban canopy: Vancouver, B.C.

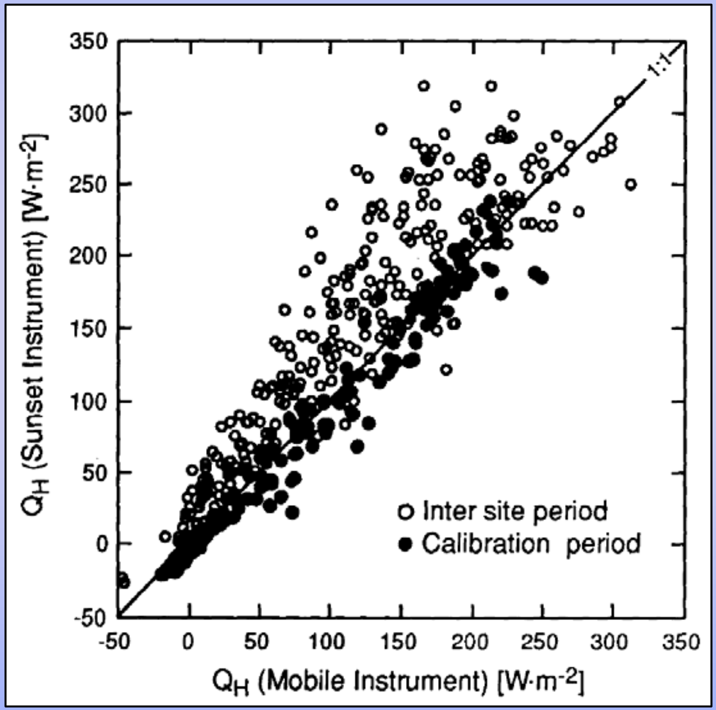


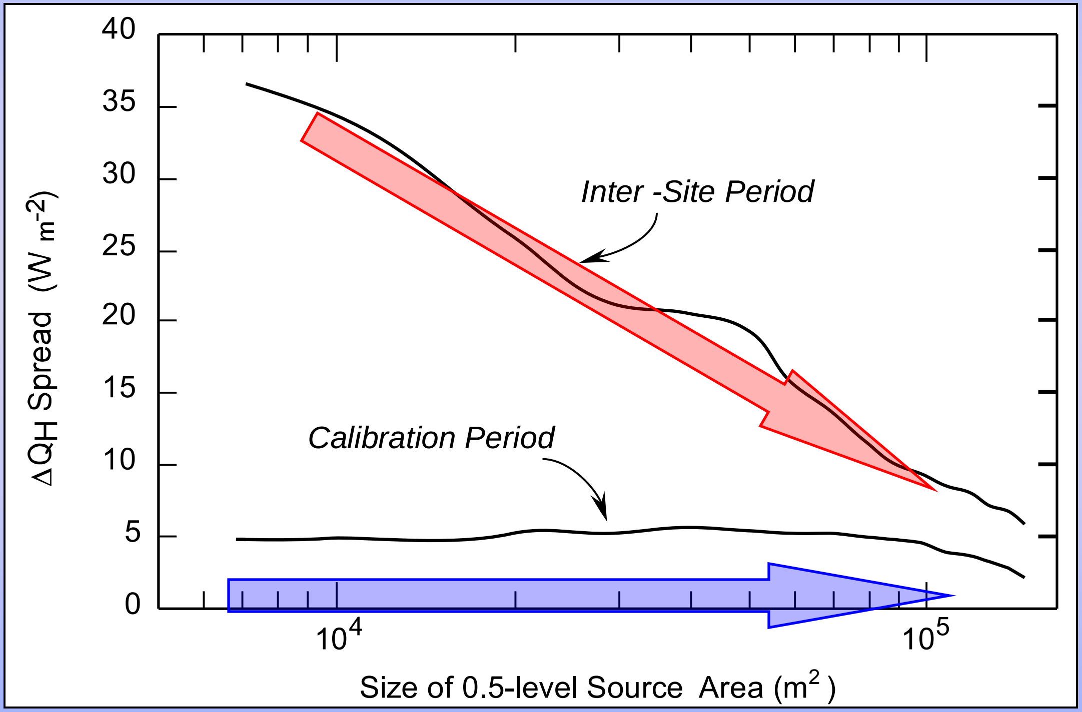
Schmid *et al.*, BLM 1991

Measured Spatial Variability of Sensible Heat Flux (Q_H) in Residential Vancouver Area (1986)

○ Q_H variations within ~ 1 km
● instrument uncertainty

Q_H variations decrease with **increasing source area** (= effective spatial averaging)

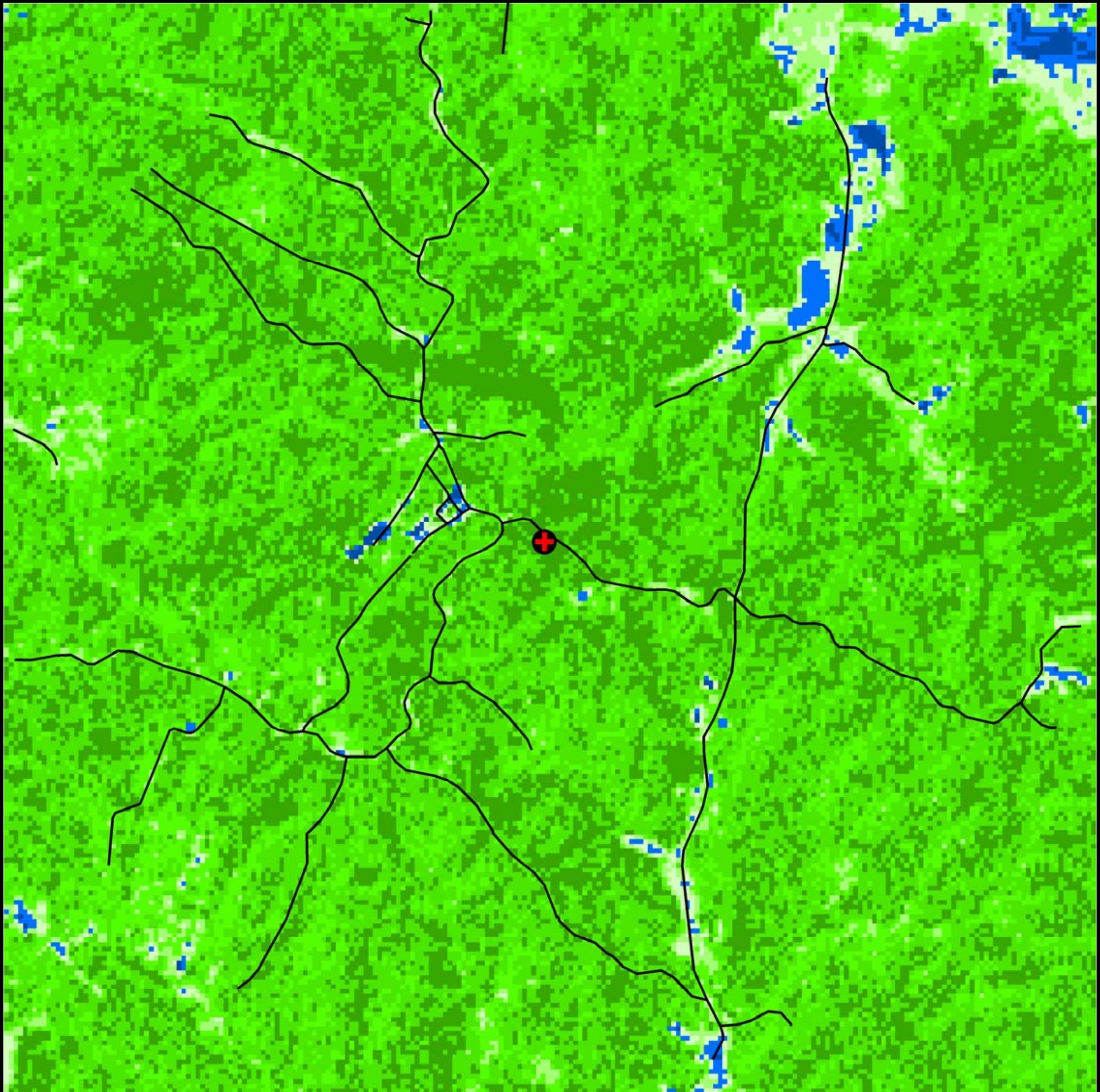




spatial representativeness

... end of excursion: back to forest!

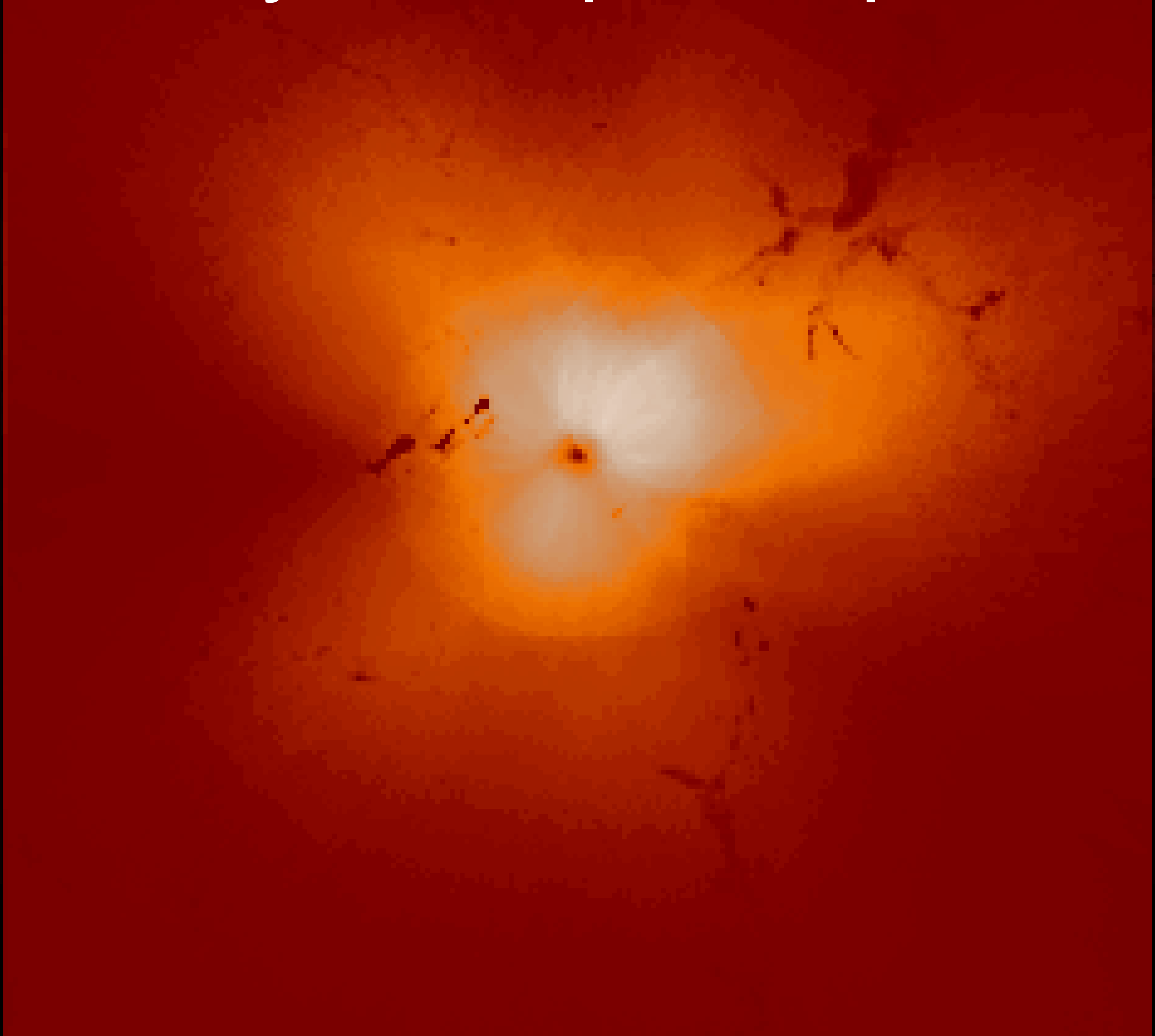
Schmid *et al.*, BLM 1991; Schmid, AgForMet 1997



Hourly Footprints 2001: YD 217- YD 225

Aug 5 – Aug 13

8-Day Flux Footprint Composite



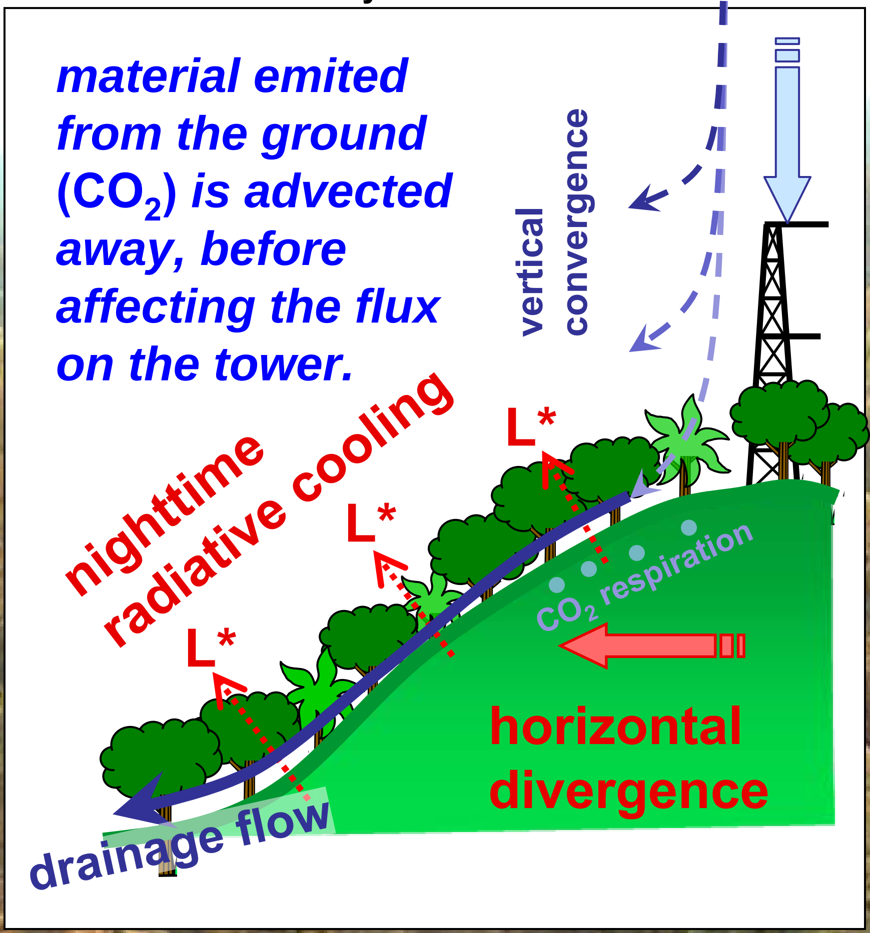
Hourly Footprints 2001: YD 217- YD 225

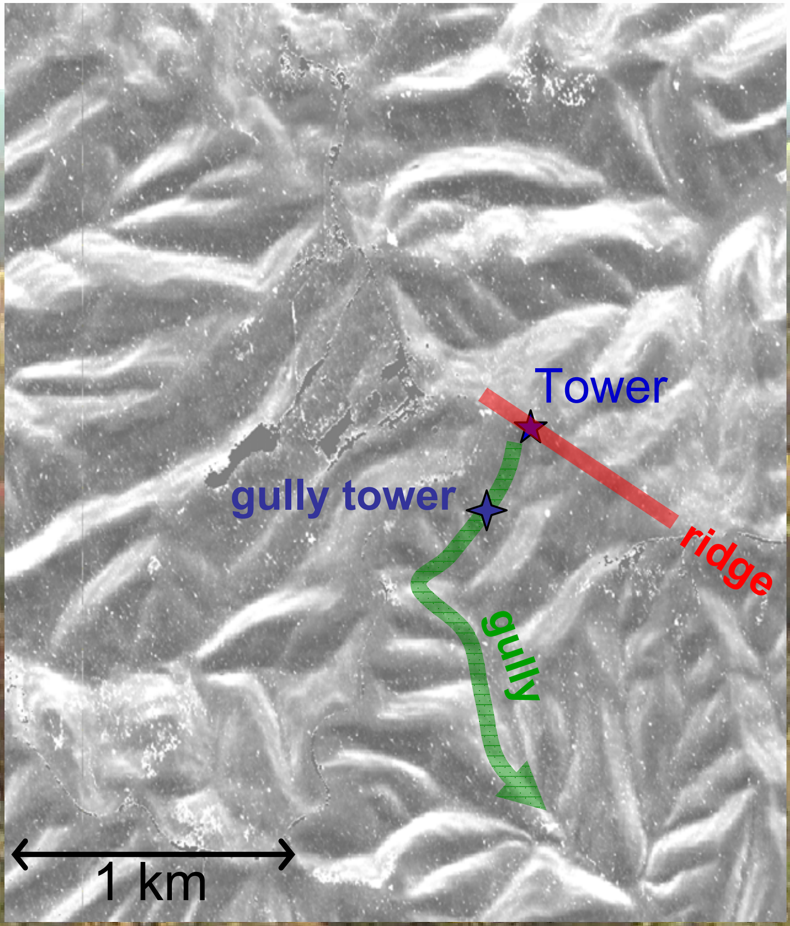
Aug 5 – Aug 13

Problem with Nighttime Fluxes in Topography?

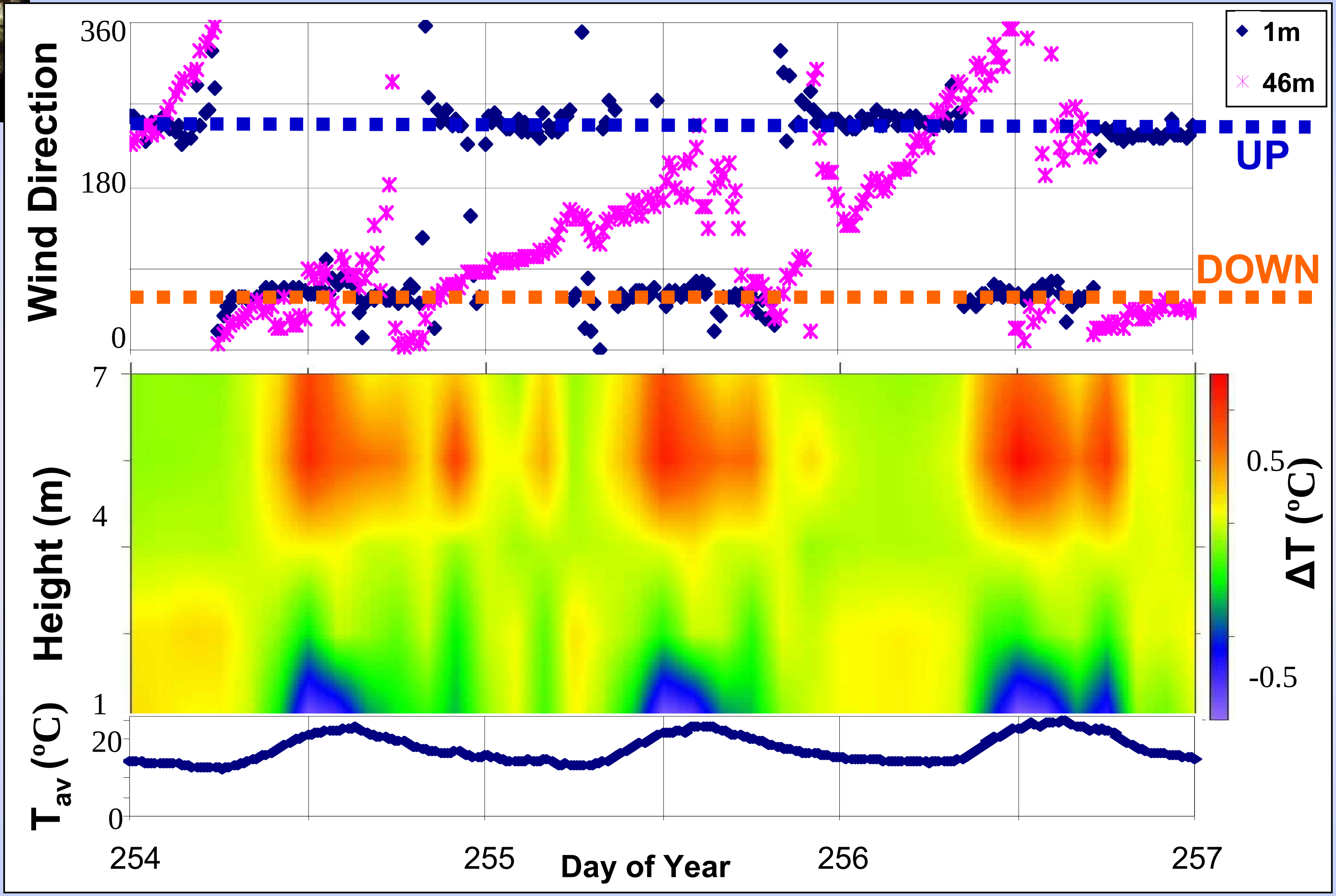
Is respired CO_2 at night "leaking" out of the box, without a trace detectable by the flux sensor?

Advection and Gully Flows in Complex Forested Terrain
N.J. Froelich, H.P. Schmid
Indiana University

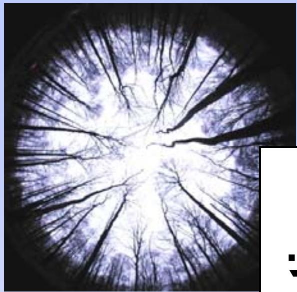




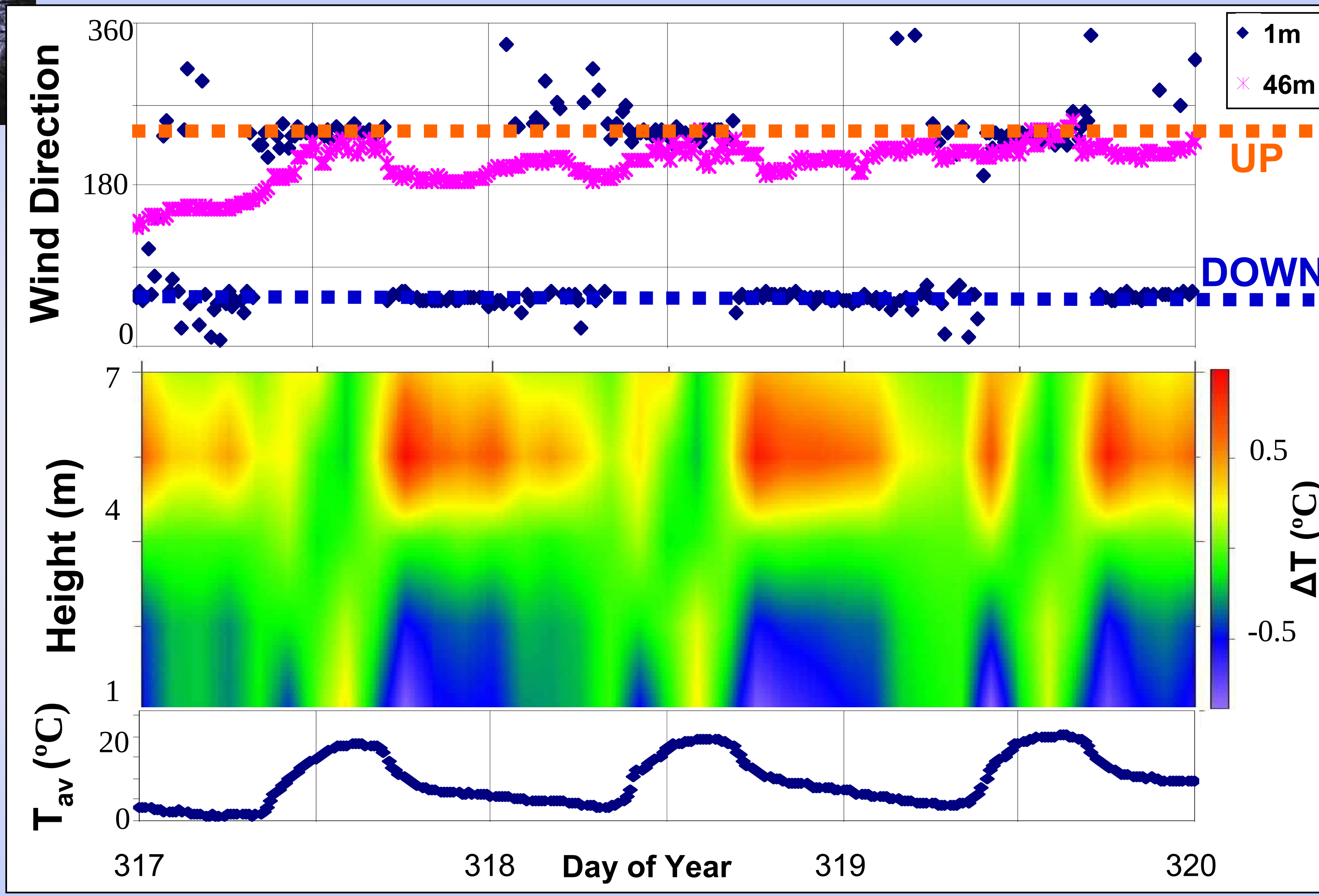
Thermotopographic Flow – Leaf-On



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

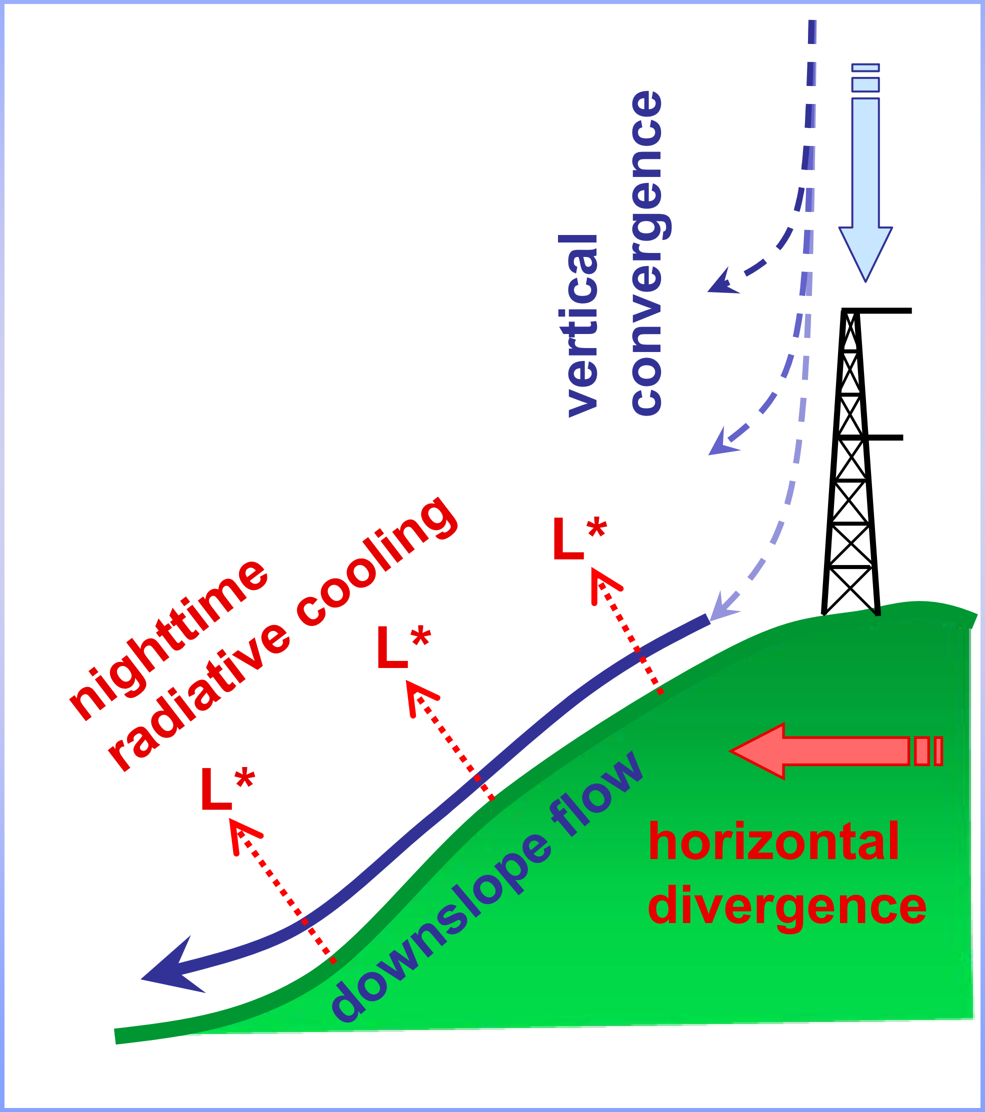


Thermotopographic Flow – Leaf-Off

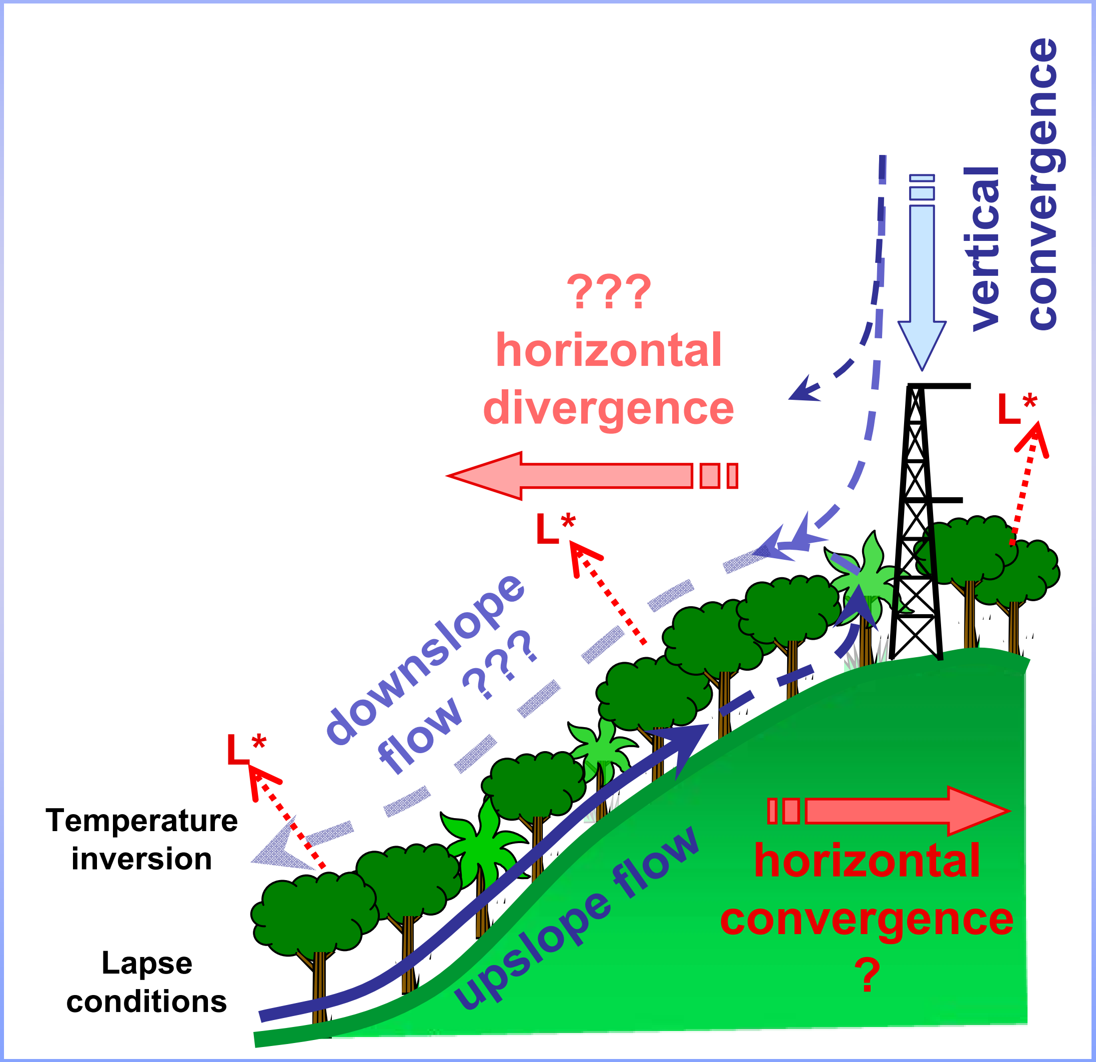


- **Night «–» Down-gully flow with inversion conditions**
- **Day «–» Up-gully flow with lapse conditions**

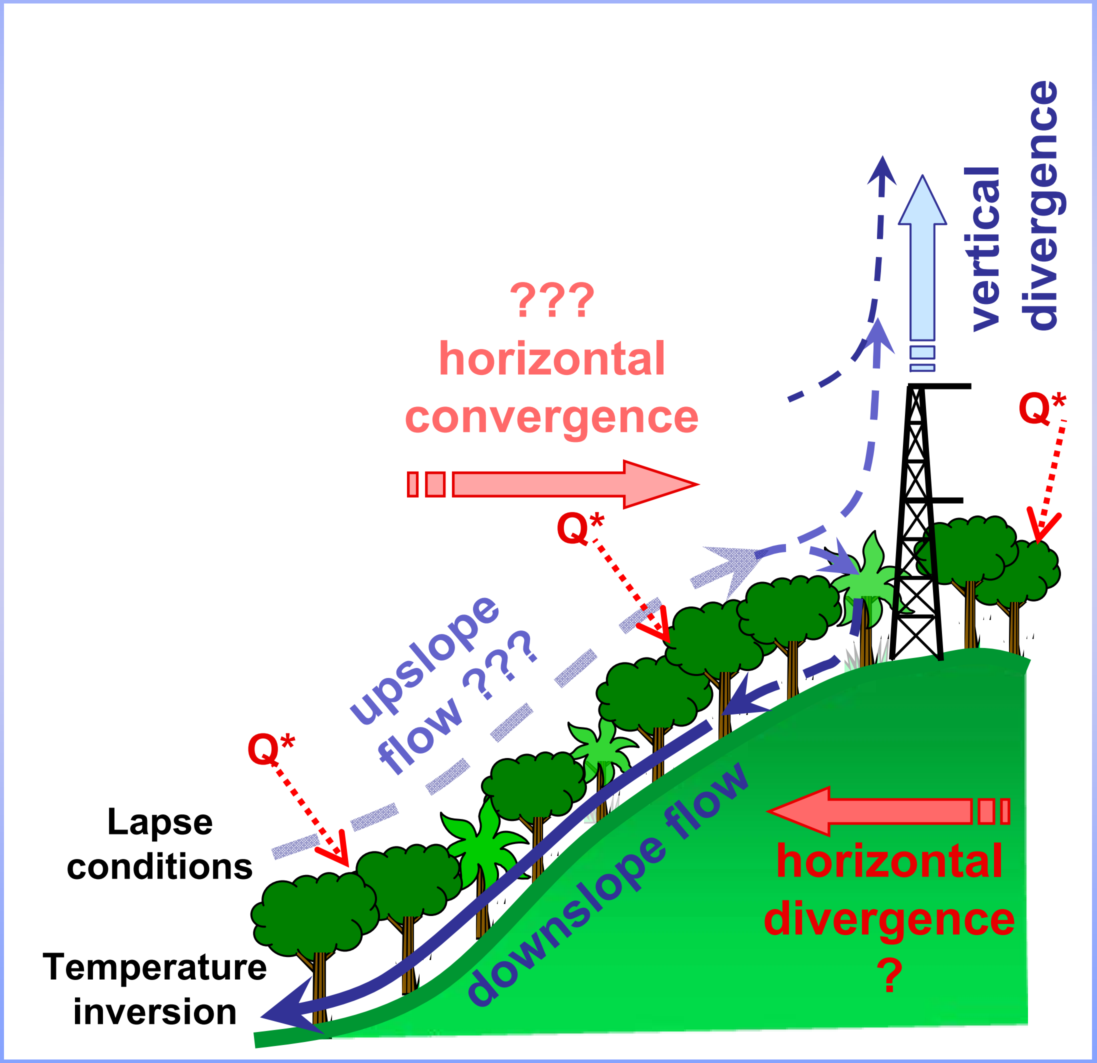
Flow Patterns: Leaf-Off Nighttime



Flow Patterns: Leaf-On Nighttime



Flow Patterns: Leaf-On Daytime



Summary

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

There are still many flow phenomena that we do not completely understand in complex terrain.

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MMSF

UMBS

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