Footprint Modelling for Flux Towers

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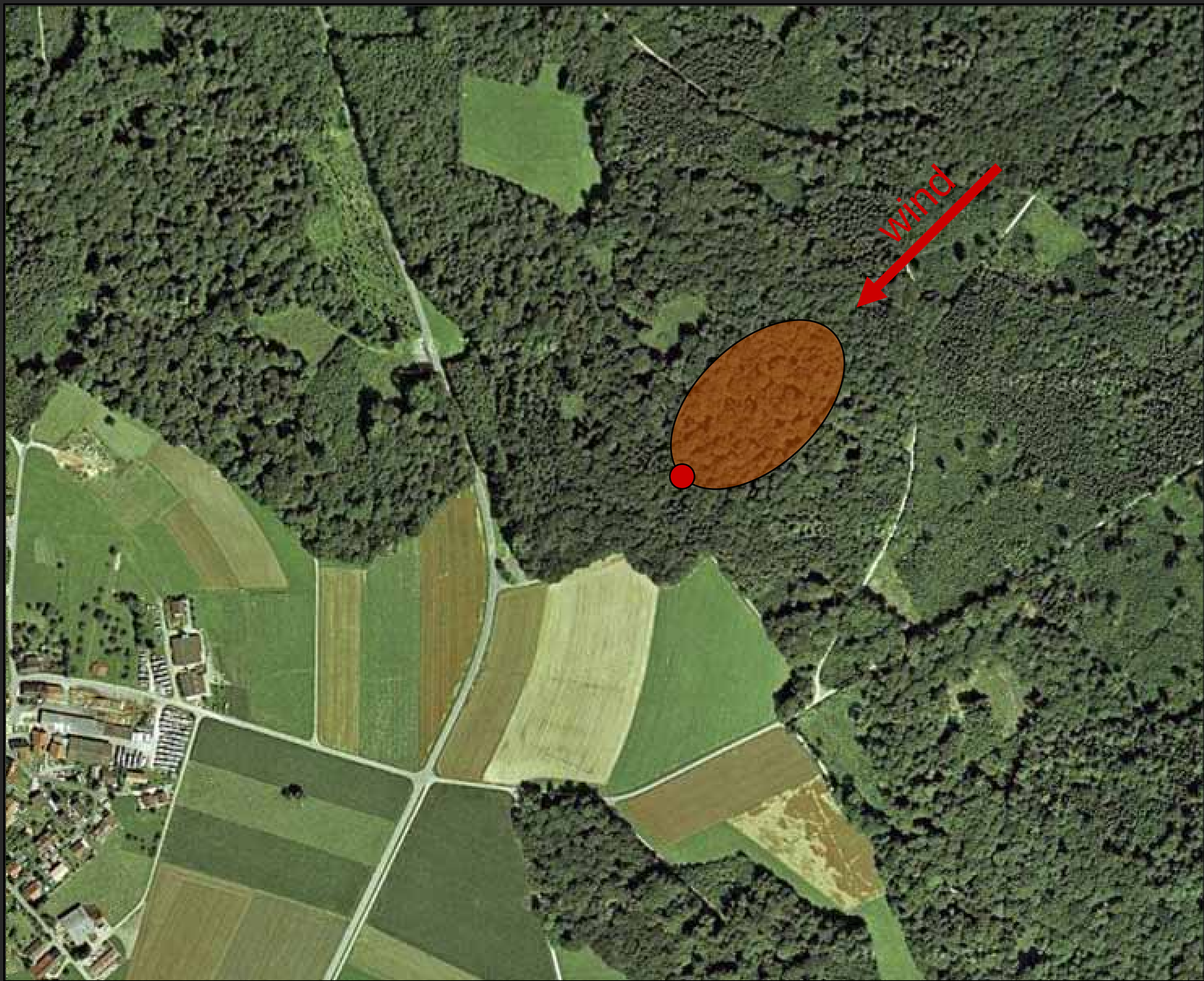
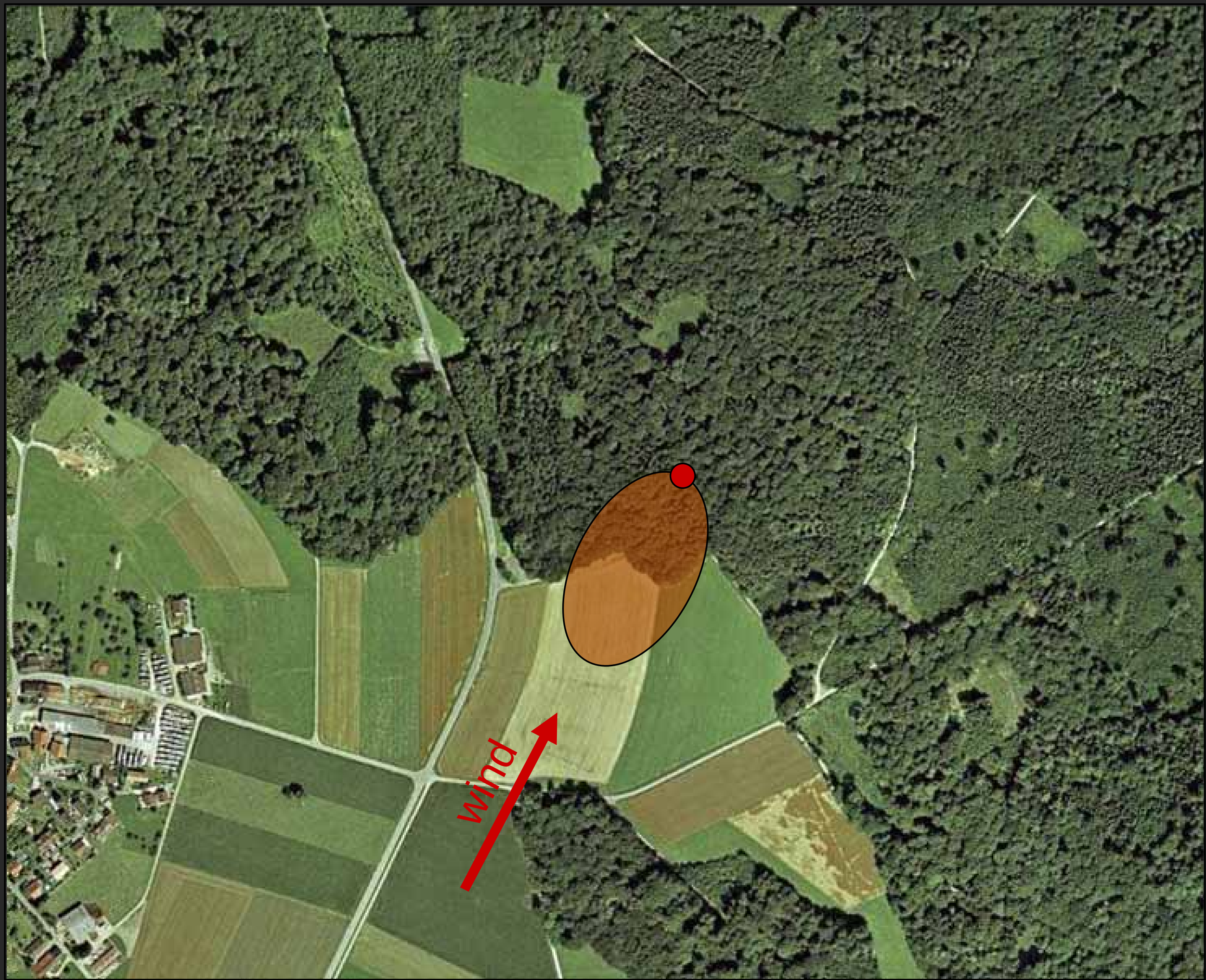
Footprint Estimates



Footprint Estimates



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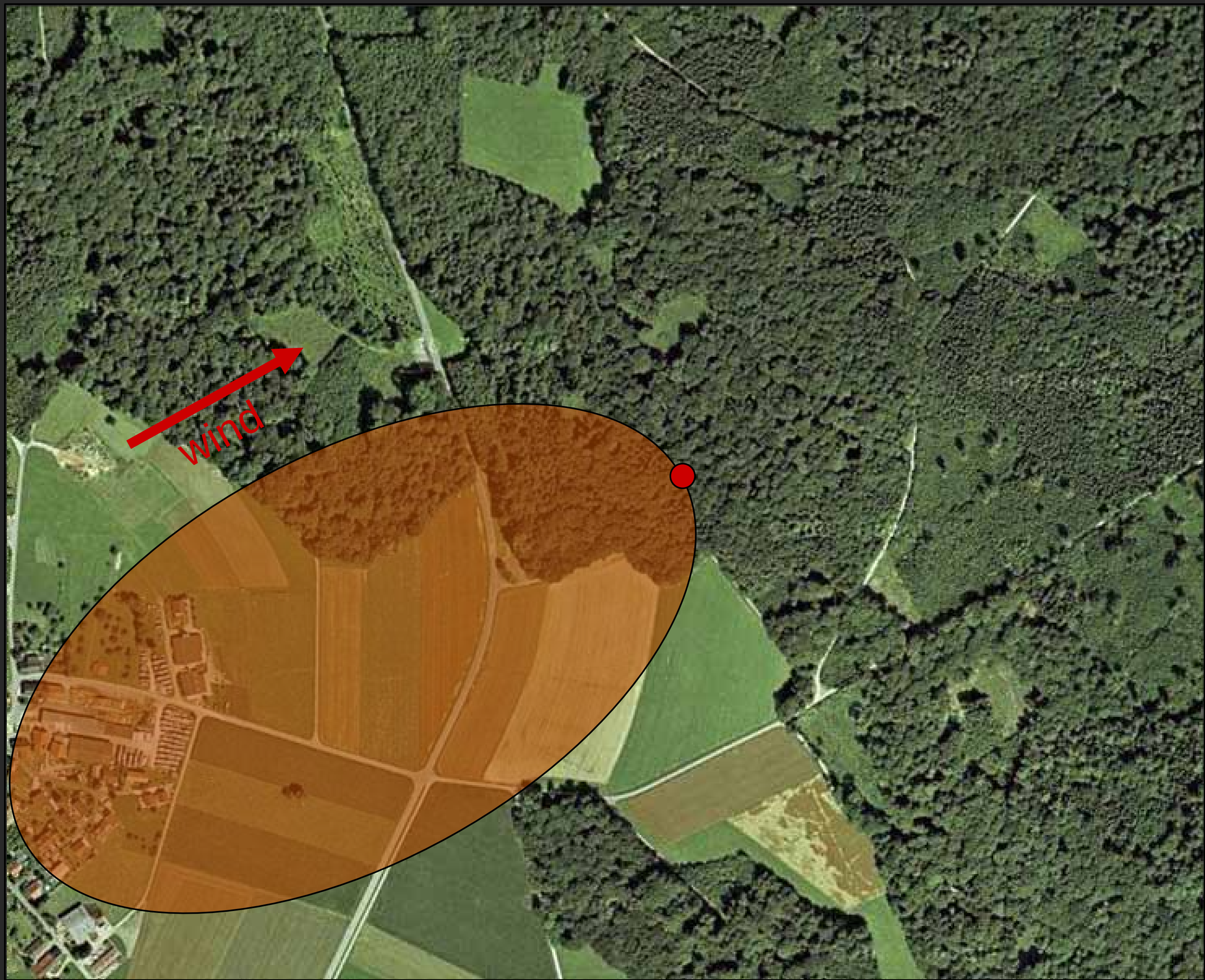
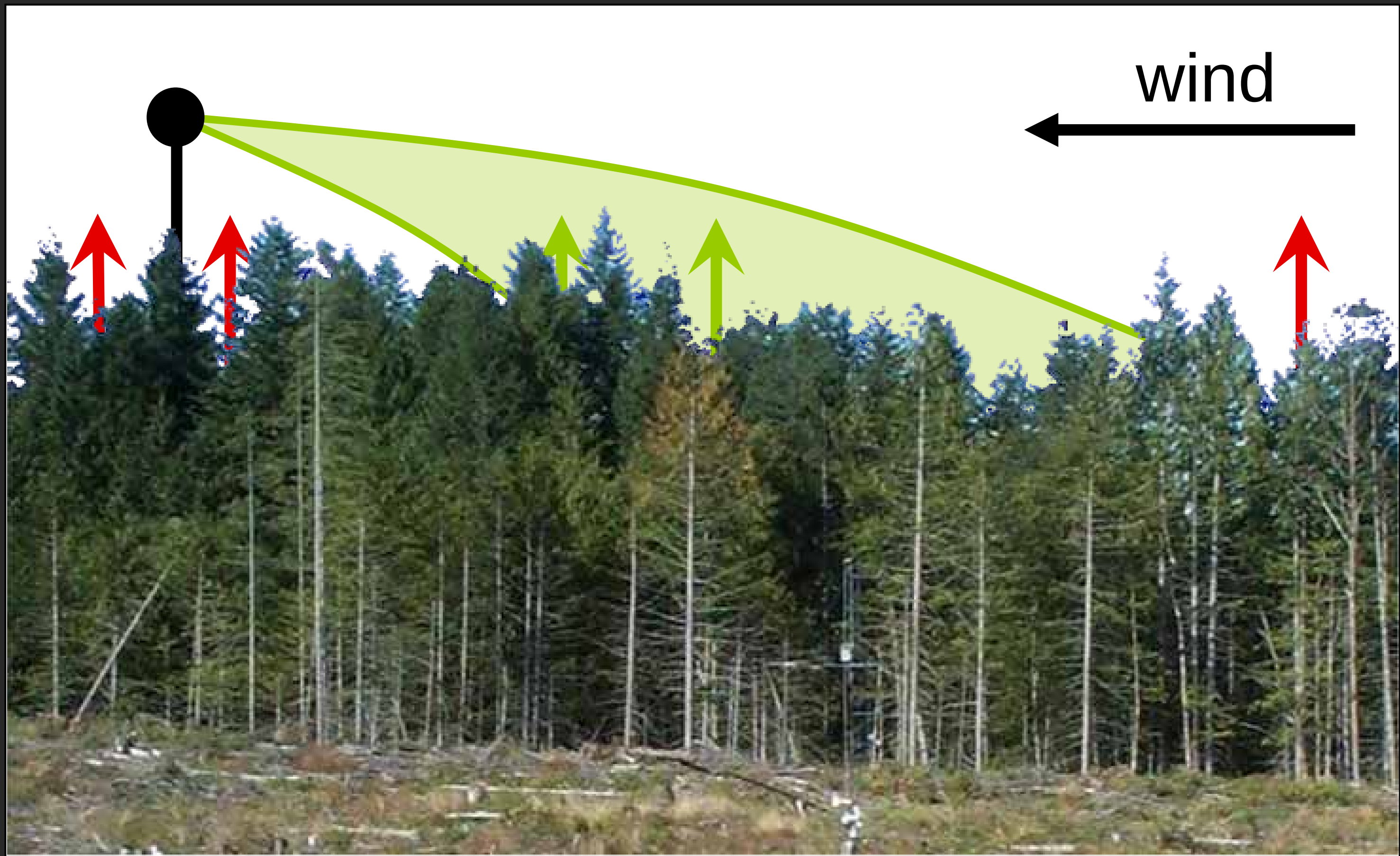


Which Area Contributes to Measurement?

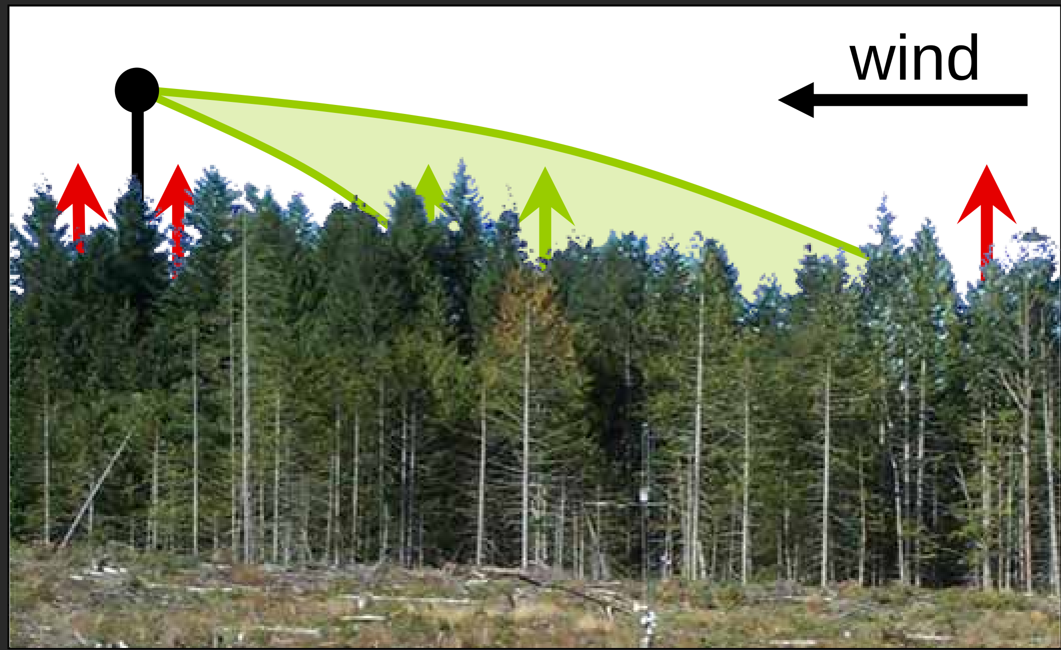
Footprint: spatial extent of the area contributing to the measured quantity



Which Area Contributes to Measurement?

Footprint depends on

- Height of measurement
- Surface properties
- Atmospheric flow characteristics (wind speed, wind direction, turbulence, atmospheric boundary layer height ...)



Footprint Estimates

Footprint description

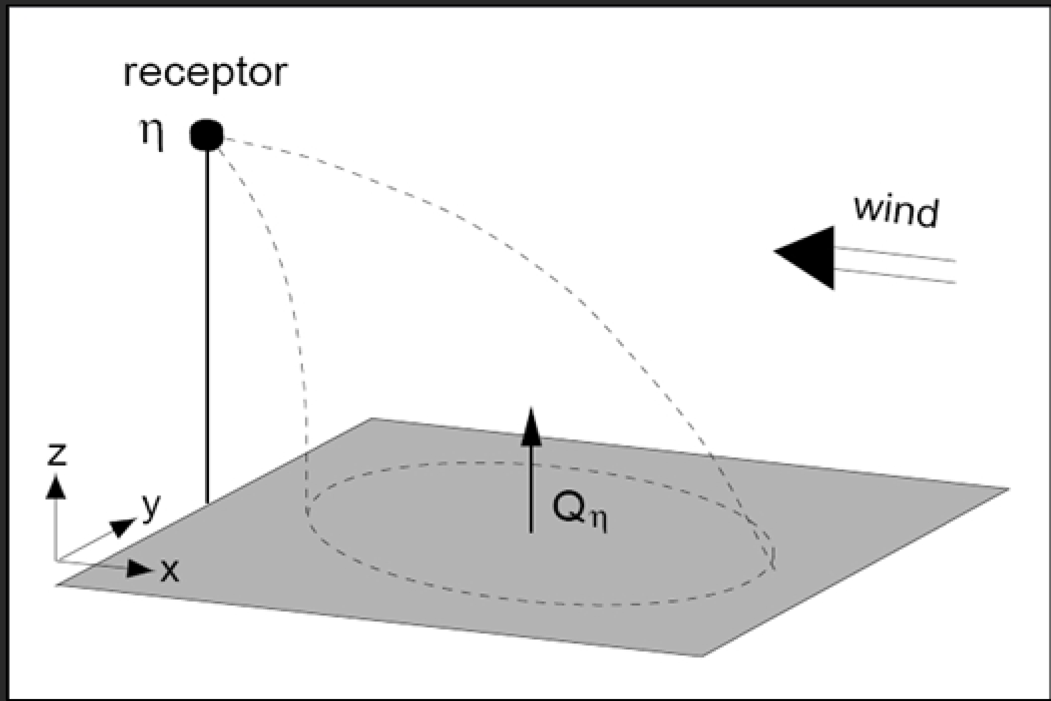
$$\eta(r) = \int_R Q_\eta(r + r')\, f(r, r')\, dr'$$

η: Measured value at *r*

Qη: source emission rate at *r*+*r'*

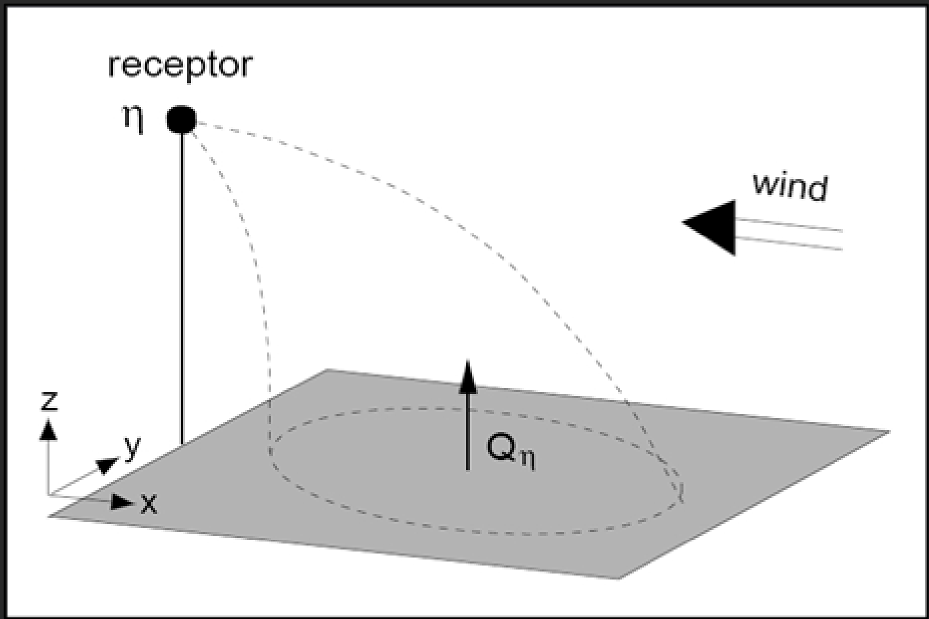
R: Domain of integration

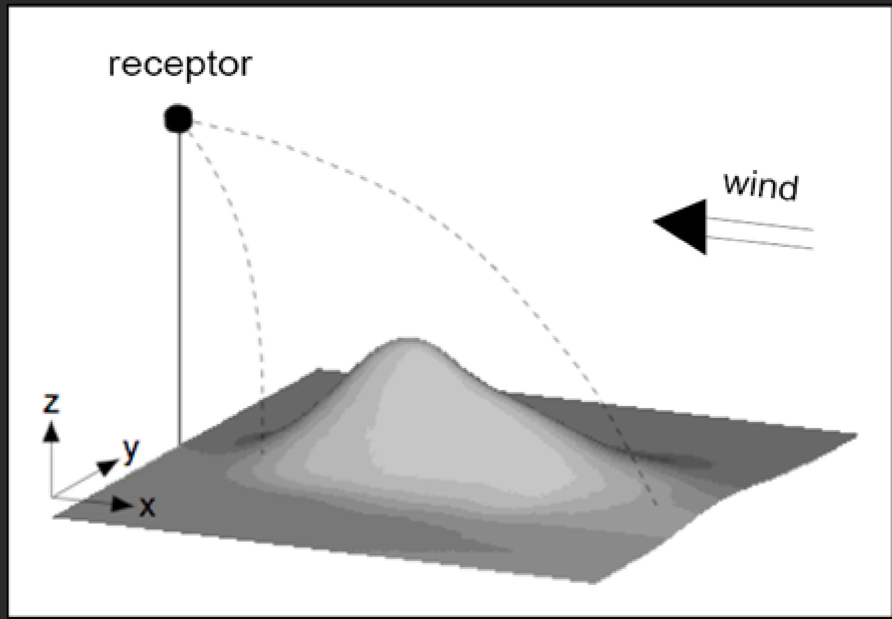
f: Transfer function (footprint function)



Footprint Estimates

Footprint function: probability density function





Footprint Estimates

Footprint description

$$\eta(r) = \int_R Q_\eta(r + r')\, f(r, r')\, dr'$$

- Analytical models
- Lagrangian stochastic particle models
- Parameterisations of above models
- Large-eddy simulations, closure model approaches

Footprint Estimates

Analytical footprint models

- approximate analytical solutions of diffusion equation applying K-theory
- examples: Schuepp et al. 1990; Schmid and Oke 1990; Wilson and Swaters 1991; Horst and Weil 1992, 1994; Schmid 1994, Kormann and Meixner 2001, etc.

→ only valid for surface layer and homogenenous surfaces

Footprint Estimates

Large-eddy simulations and closure model approaches

- Navier-Stokes equations, resolving large eddies while parameterizing subgrid-scale processes
- applicable on heterogeneous terrain and complex boundary conditions
- each simulation for one specific flow pattern
- examples: Leclerc et al. 1997; Sogachev et al. 2002; Sogachev and Lloyd 2004

→ highly CPU-intensive

Footprint Estimates

Lagrangian stochastic particle models

- in most cases assuming Gaussian turbulence
- backward mode is applicable on heterogeneous terrain
- examples Gaussian: Leclerc and Thurtell 1990; Horst and Weil 1992; Flesch et al. 1995, 1996; Baldocchi 1997; Rannik et al. 2000, 2003; etc.
- example stable to convective conditions: Kljun et al. 2002

→ CPU-intensive

Footprint Estimates

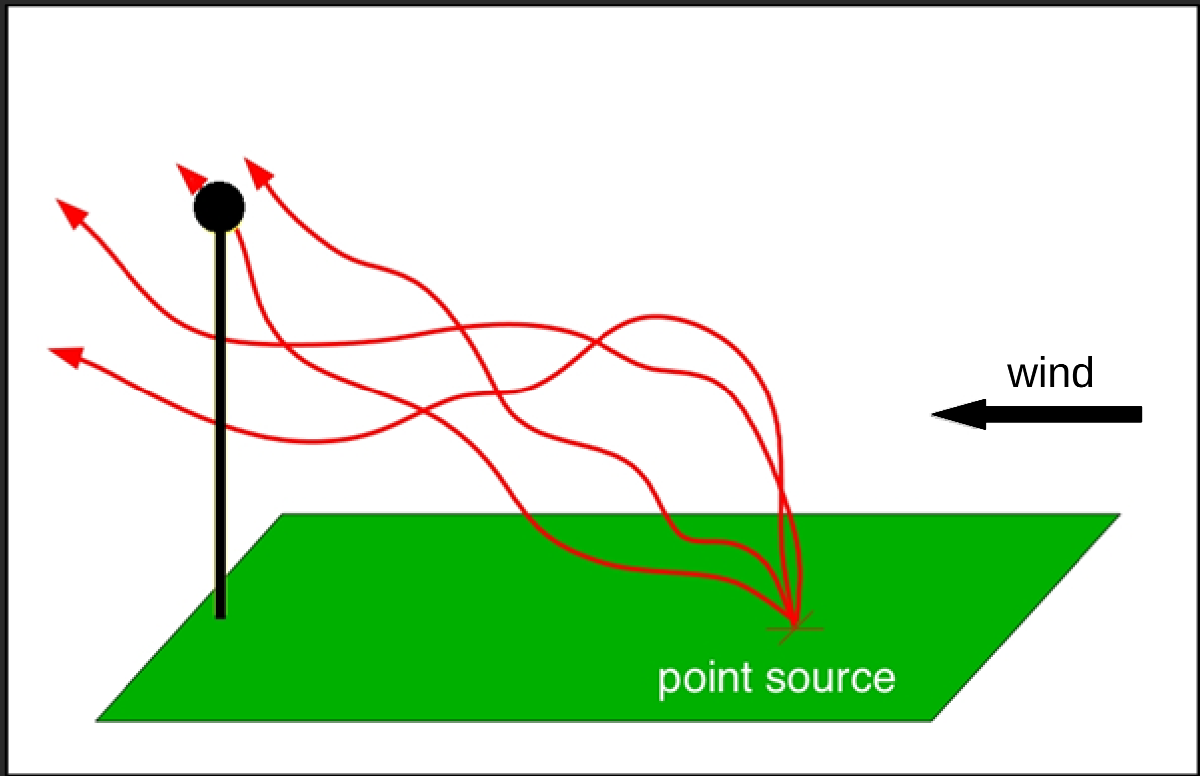
Parameterisations of Lagrangian stochastic particle models

- simple parameterisations of Lagrangian model results
- examples: Hsieh et al. 2000; Kljun et al. 2004

$\rightarrow$ fast but simplified, may only be valid for specific atmospheric conditions

Lagrangian Stochastic Particle Models

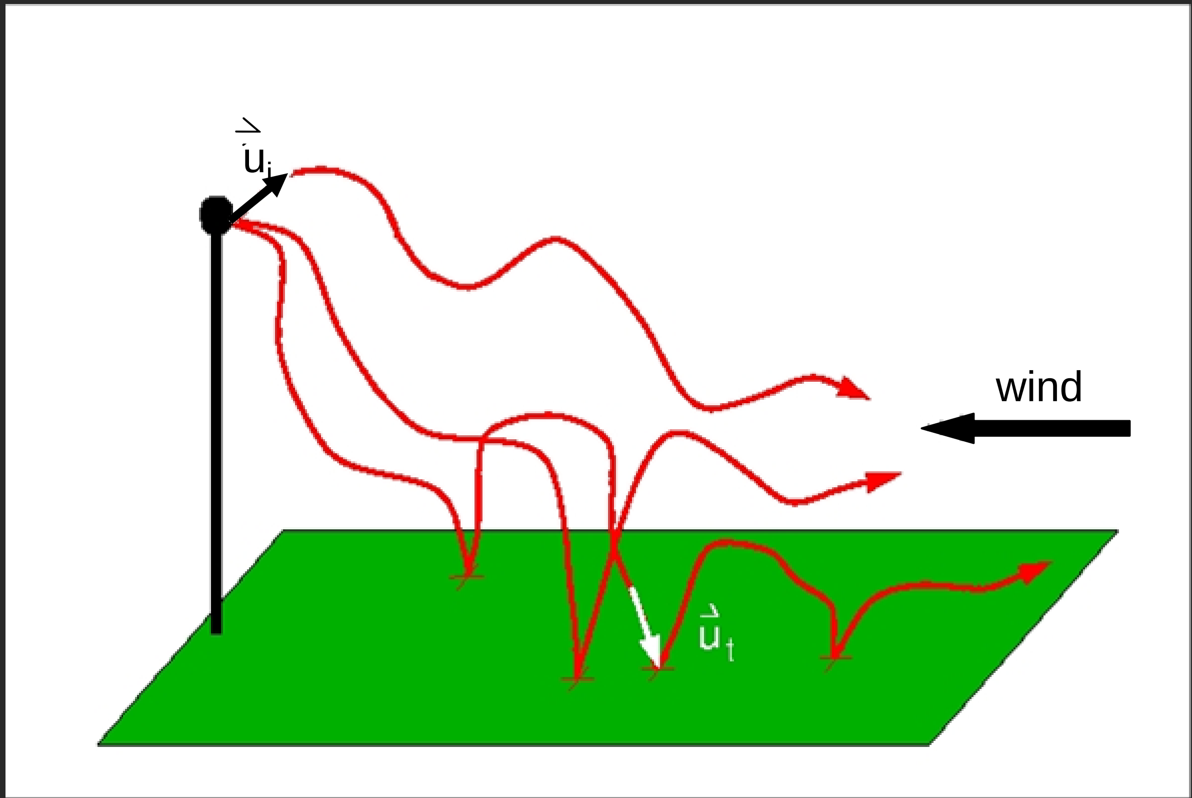
Lagrangian stochastic particle models: forward mode



Evaluate many point sources and sample particle tracks at sensor height.

Lagrangian Stochastic Particle Models

Lagrangian stochastic particle models: backward mode



Start particle tracks at sensor location.

Capable of dealing with heterogeneous surfaces.

Lagrangian Stochastic Particle Models

Langevin equation (Thomson 1987):

Lagrangian particle position $\mathbf{x} = (x, y, z)$

Lagrangian particle velocity $\mathbf{u} = (\overline{u} + u', v', w')$

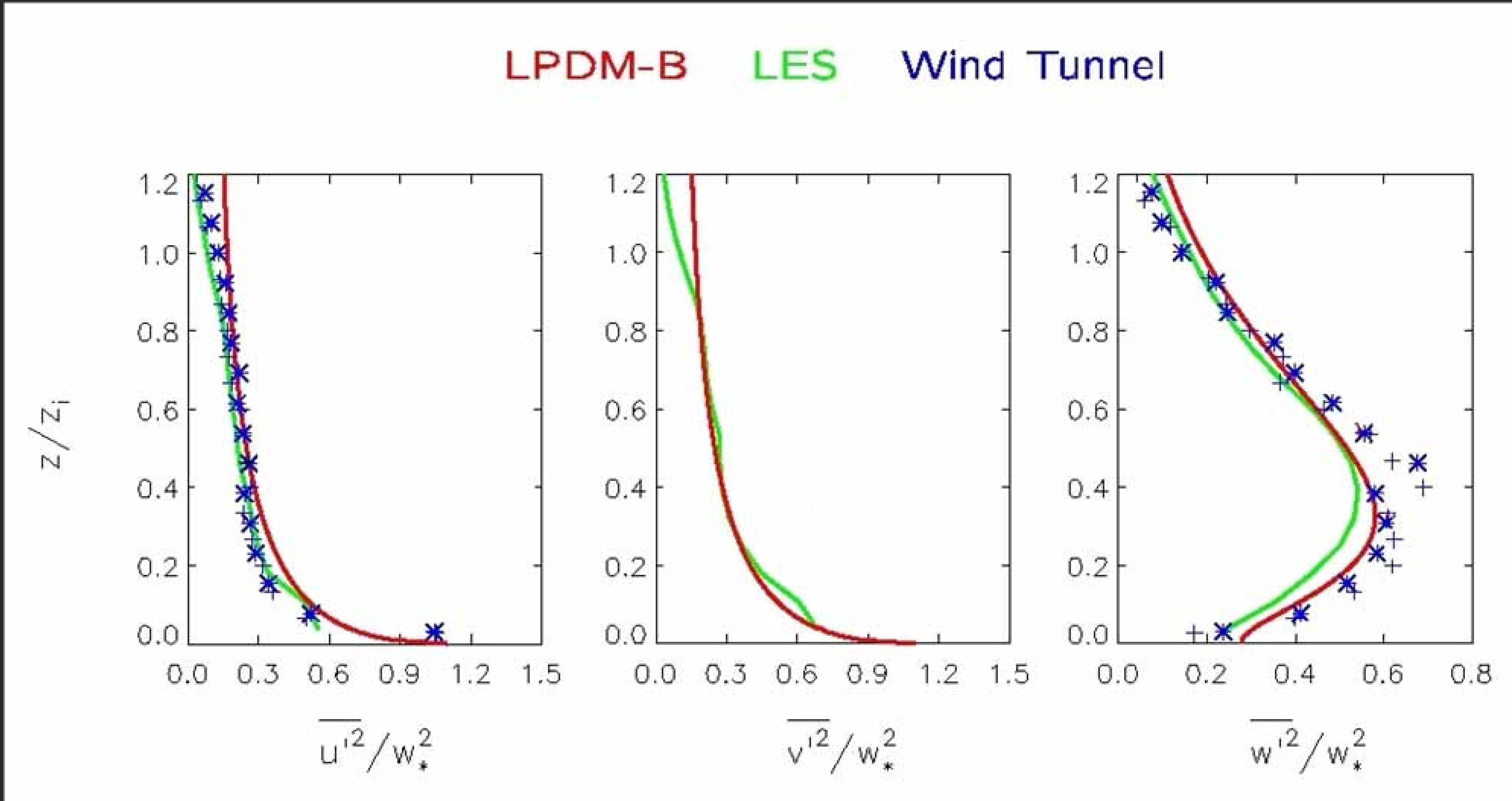
$$
\begin{aligned}
\mathrm{d}u'_i &= a_i(\mathbf{x}, \mathbf{u}, t)\, \mathrm{d}t + b_{ij}(\mathbf{x}, \mathbf{u}, t)\, \mathrm{d}\xi_j \\
\mathrm{d}\mathbf{x} &= \mathbf{u}\, \mathrm{d}t
\end{aligned}
$$

Correlated part depending on turbulent velocity a_i

Uncorrelated random contribution b_{ij}

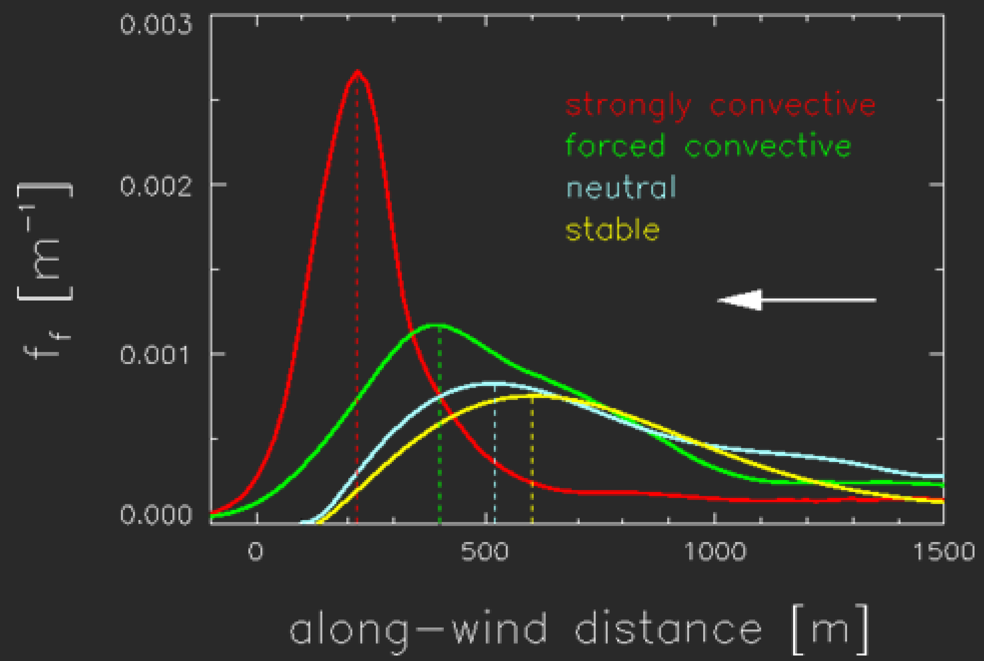
Lagrangian Stochastic Particle Models

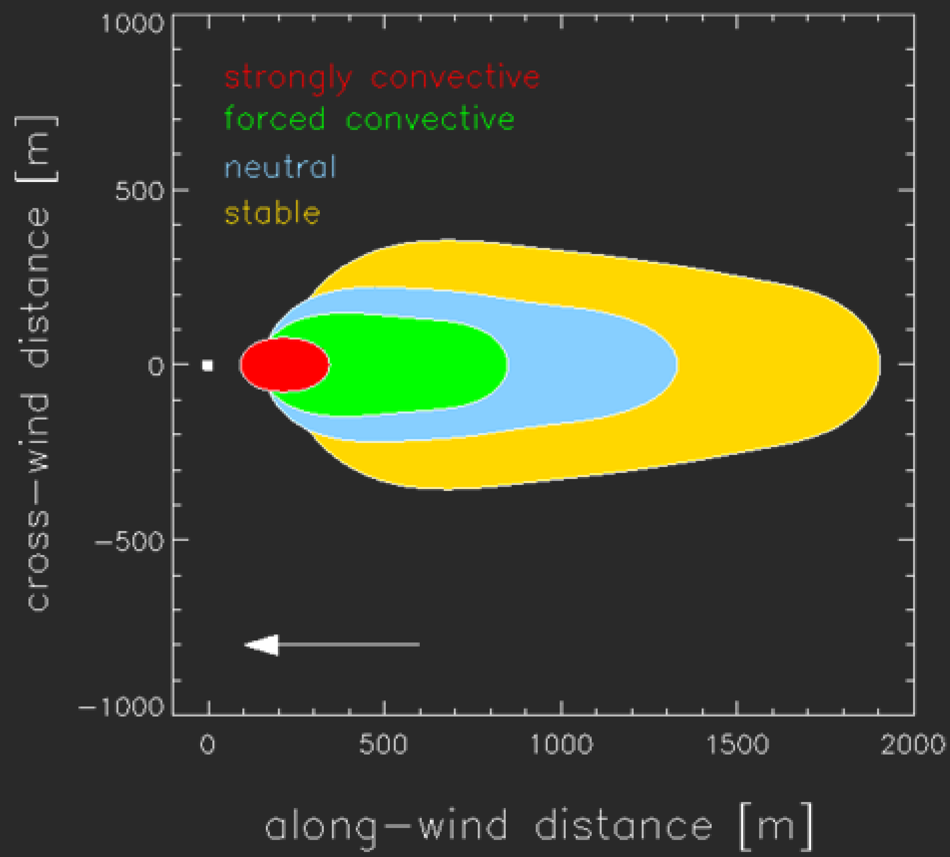
Turbulence profiles as input



Footprint Estimates

Impact of atmospheric stability conditions

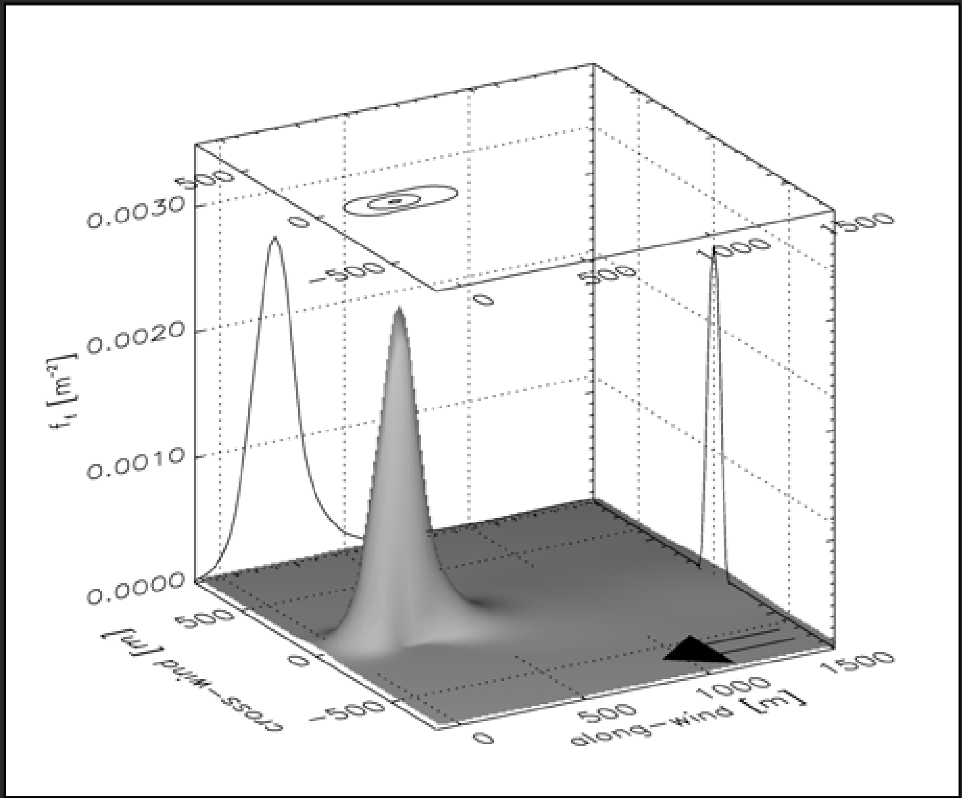




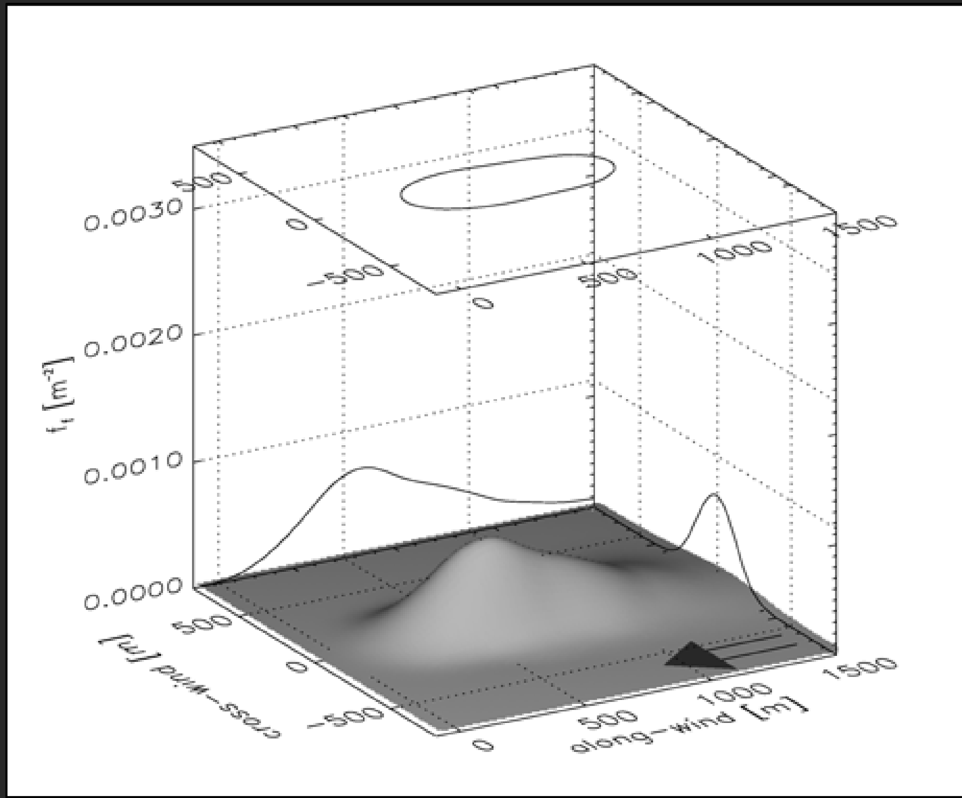
Footprint Estimates

Impact of atmospheric stability conditions

strongly convective

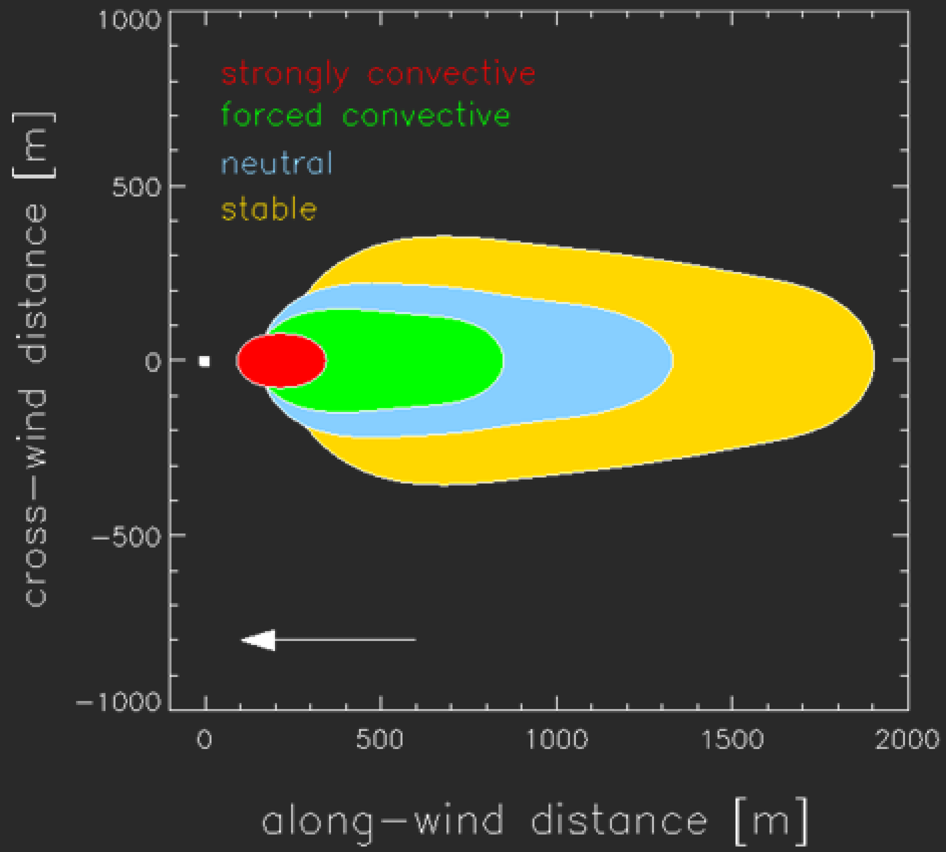


stable

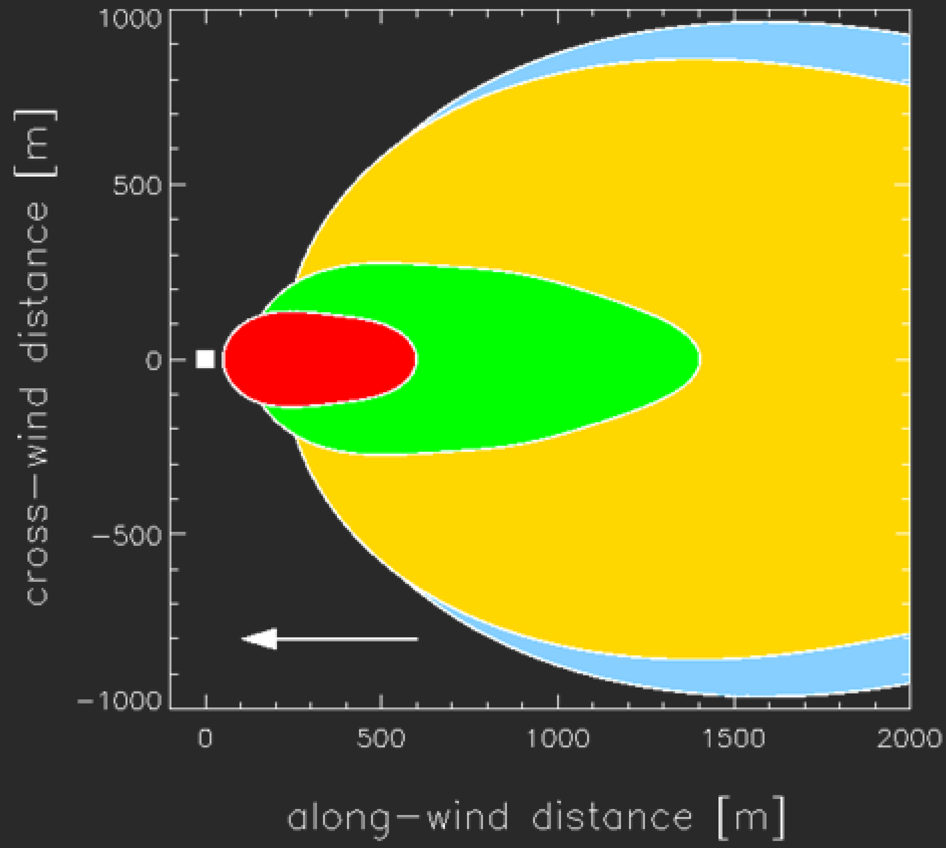


Footprint Estimates

Flux and concentration footprints: latter tend to be longer

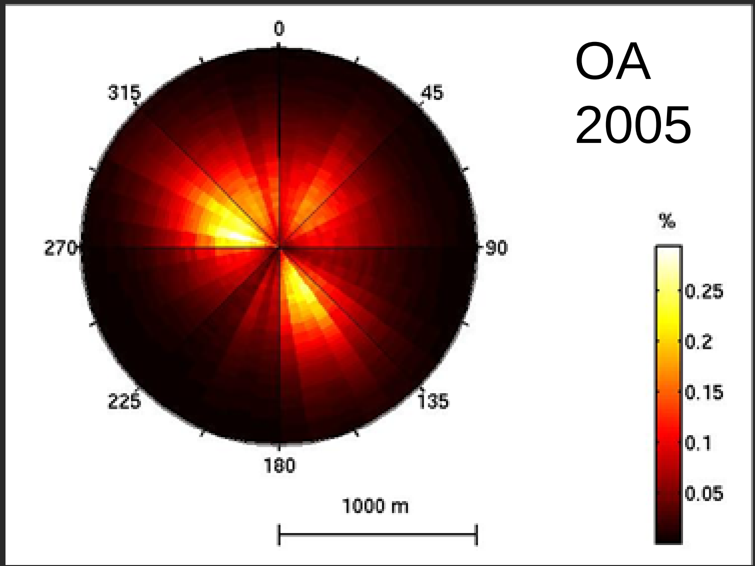


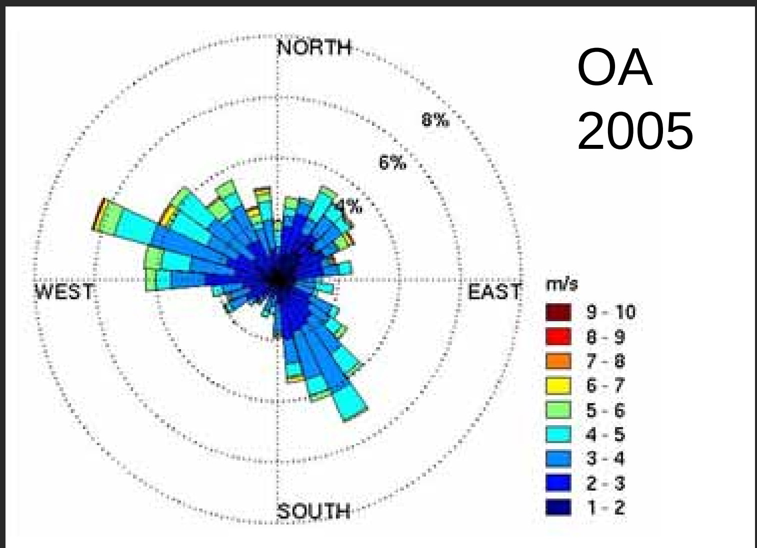
Flux Footprint



Concentration Footprint

Footprint Climatology





- One footprint for each flux data point
- Consider all data points within study period (months, years)
- Cumulate / aggregate spatial weighting from footprints

Example: Tall Tower Study

Study Site & Land Cover

- TV/radio tower near Hegyhátsál, western Hungary
- Rural agricultural region
- Fairly flat terrain
- Eddy covariance system at 82 m height
- Study period: 2003 to 2008

Barcza Z., A. Kern, L. Haszpra, N. Kljun, 2009, Agric. Forest Meteorol. 149, 795 – 807

Example: Tall Tower Study

Methods

- Footprint climatology
- Characterise crop type (summer vs. winter) using MODIS NDVI (MOD13) at 250 m spatial resolution
- Quantify contribution of crop types by integrating crop coverage maps with footprint climatology
- Attribute measured NEE to crop type (C4 / C3)

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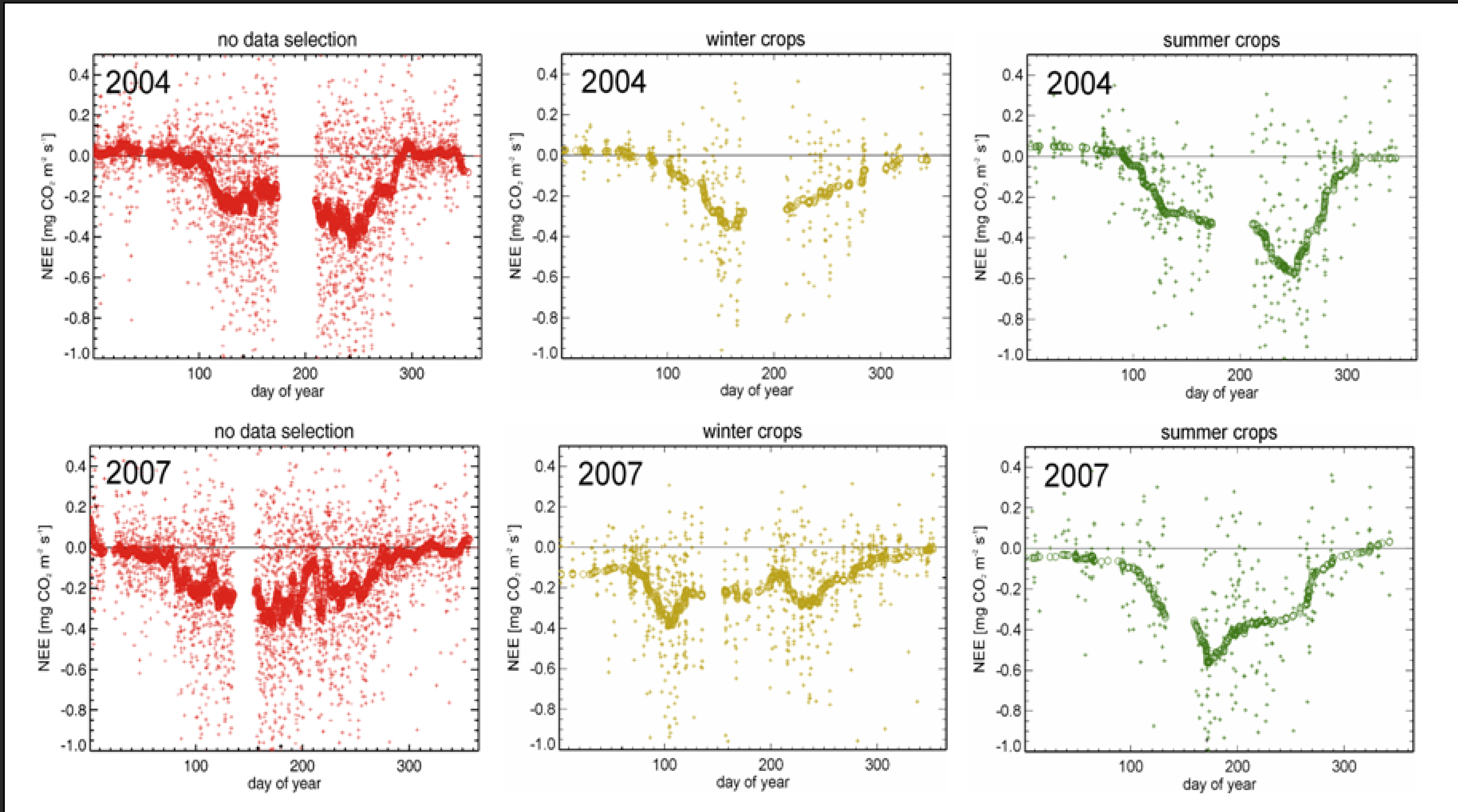
Example: Tall Tower Study

Measured total NEE and derived crop-specific NEE



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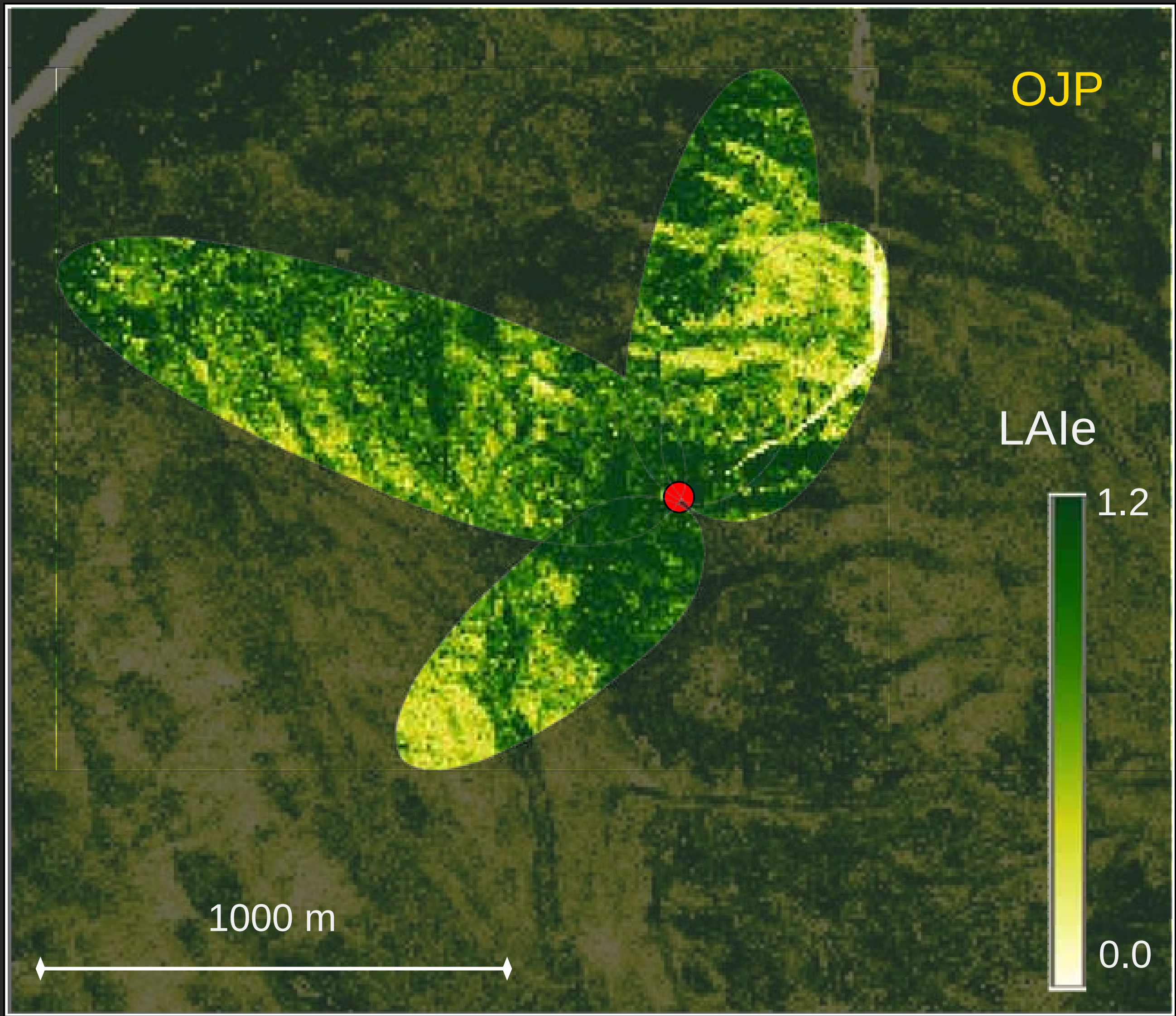
Combination of LiDAR Data and Flux Data



Combination of LiDAR Data and Flux Data

- Footprints for each flux data point
- Maps of canopy characteristics from LiDAR survey
- Extract canopy characteristics within footprints

→ tree height, canopy depth, LAI etc. per data point

→ Comparison of CO_2 fluxes and canopy characteristics

→ What trees are measured, how do they look like?

Summary

- Footprints estimates for setting up flux tower sites, quality control and interpretation of flux data
- Issues with site heterogeneity and non-stationary flow
- Individually best suited footprint model depending on
    - flux site
    - sensor location
    - atmospheric conditions
    - temporal and spatial resolution