Some Problems on the Retrieving

Area Averaged Fluxes over Heterogeneous Surfaces

with a brief intro. to Scintillometry

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30 years Land Surface Process Experiments & 20 years World-wide Flux Networks

Objectives:

1) Better Understanding the Land Surface Processes
2) Better Prediction of the Climate

Achievements:

1) Developments of obs. technology, remote sensing,…
2) Massive data collection and exchanges. Registered stations in Fluxnet are about 1000.
3) Analysis & understanding of some major processes
4) Developments of LSM & other atm-hydro-eco models.

Shortcomings / Lessons

1) Data sharing? Exchanged data with enough description, esp., quality, uncertatainty & representativeness flagging? The effects of sensor/environmental change on long-term analysis?
2) Coordinated & synthetic studies in various flux networks, even within one station? Tempo-spatial extended analysis are less; only selective analysis done in many stations. Generality of our findings?
3) Model Data Fusion (MDF). Coordination, links between modelers & observers are weak. One of the major problems: *Scale mismatch between modeling and data*.

Representativeness of flux towers

- Based on 'footprint' analysis, representative scale of flux sites is mostly 100 m - 1 km.
- This limitation is more serious over complex surfaces. Actually, natural surfaces are almost all complicated and heterogeneous.

Model grid/ pixel scale area averaged fluxes are needed

- Flux analysis (ET and CO_2 budget etc.) on a regional or river basin scale is generally done by using numerical models. Model grid size is generally 1 - 50 km.
- Pixel size of most useful satellite images: ~1 km; for passive microwave remote sensing: 10 - 50 km .
- Model input parameters, validation of model outputs, are all on the basis of surface practical observations. The issue of Scale Matching …

Observation of area averaged fluxes

Flux Matrix

$$F_x = \sum A_i F_{x_i}$$

Scintillometry

$$F_x \sim \frac{C_x^2}{\varphi_x(z/L)}$$

Air vehicles

$$F_x \sim \langle w'x' \rangle$$

Remote sensing

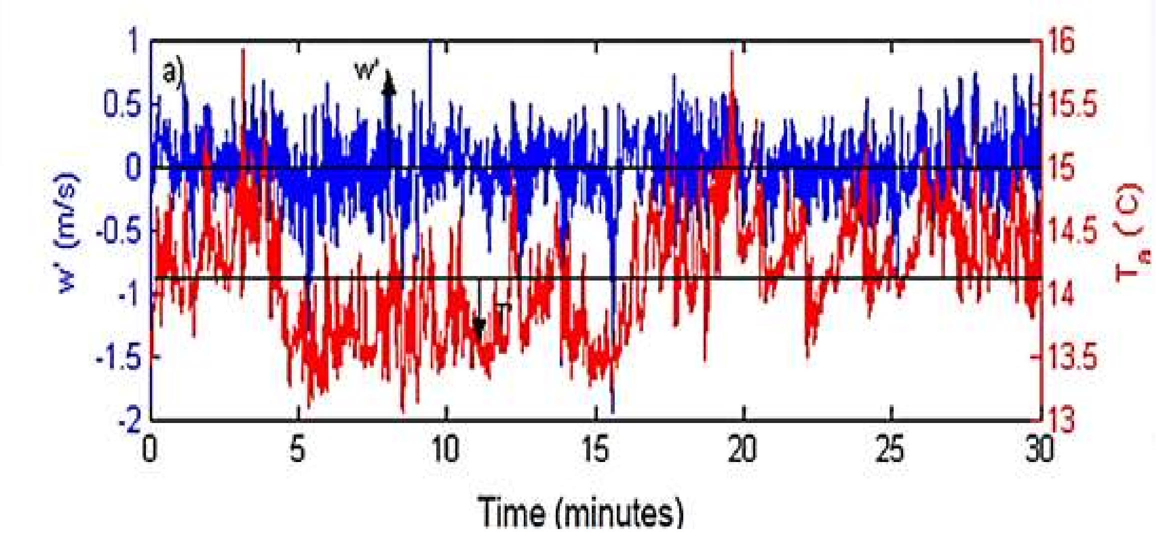
$$F_x \sim f(r, T_s, VI)$$

Flux matrix based on mainly Eddy-Covariance methods (EC)

- EC, a direct method to get fluxes based on fast samplings (10-20 Hz) of wind speed, temperature, concentrations of H_2O, CO_2, etc.
- Advantages: high accuracy, robust, reliable in 'long-term' operation.
- The dominant method used in all flux stations, and, a generally accepted standard in flux measurement.

Eddy-Covariance methods

Observation: time series of vertical wind speed & scalers, e.g. *T*



$$w = \overline{w} + w'$$

$$T = \overline{T} + T'$$

$$Flux = w \cdot T$$

$$= \overline{w}\overline{T} + \overline{w'T'}$$

$$\approx \overline{w'T'}$$

$\Rightarrow$ Sensible heat flux: $H = \rho C_p \overline{w'T'}$ [W/m^2]

Similarly,

Momentum flux:	$\tau = -\rho\overline{u'w'}$	[kg/ms^2]
Latent heat flux:	$\lambda E = \lambda\overline{w'\rho_w{}'}$	[W/m^2]
CO_2 Flux:	$F_c = \overline{w'\rho_c{}'}$	[mg/m^{2}s] or [μmol/m^{2}s]

…

Limitations of EC & its flux matrix

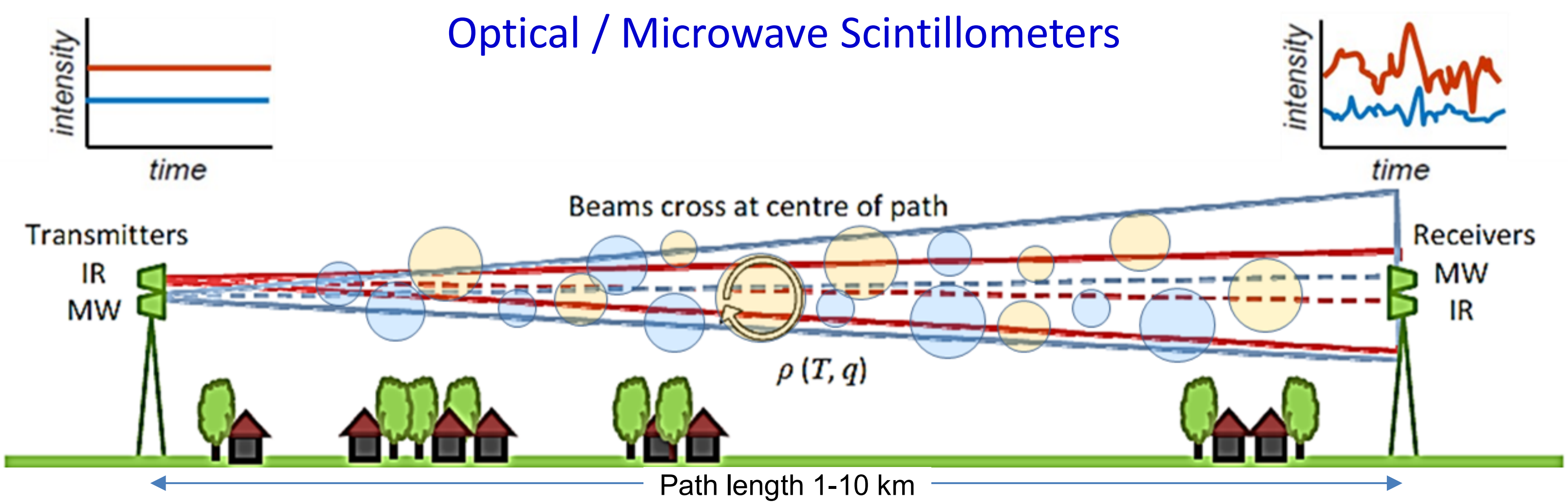
- Higher requirements on atmospheric environment
  - Stationary of atmosphere status
  - Development of atmospheric turbulence
  - Horizontal & homogeneous surface ($\overline{w} = 0$)
  - Observation in the constant flux layer (ASL)
  - Contribution from all scale eddies are captured, i.e., fast enough sampling & long enough averaging period ...

  When the conditions are not satisfied …
  - Using sophisticated corrections in data processing
  - Quality control of data products (which generates lots of data gaps in flux time-series, esp. over complex surface).
- Limitations of spatial representativeness
  (generally, ~10^2 m for a single site)
- Data integration of point measurements to an accurate representation of areal fluxes is not straight forward.

Scintillometry

A new technology operated since mid-1990s

- A convenient method to measure fluxes at 1-10 km scale
- Eddies with various *T* & *q* induce light scattering (refra./diffraction).
  Fluctuation of light intensity → Intensity of turbulence → Fluxes
- Interdisciplinary of
  Turbulence + *Wave propagation* + *Micrometeorology*



2 important parameters in turbulence: Spectra & Structure Parameters

- Based on Kolmogorov local isotropy turbulence
- 2 related turbulence parameters $(x, y = n, T, q, \ldots)$
  - **Spectra**: 3-D spectra in inertial sub-range

    $$\Phi_x(\kappa) = 0.033\, C_x^2\, \kappa^{-11/3}$$

  - Structure functions

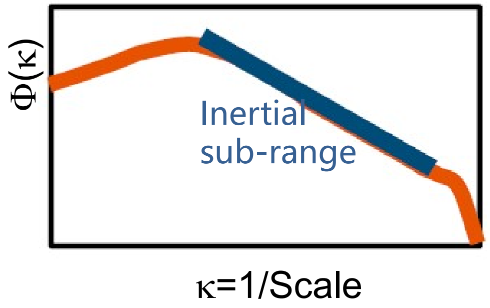
    $$D_x(r) \equiv \overline{[x(r_0 + r) - x(r_0)]^2}$$

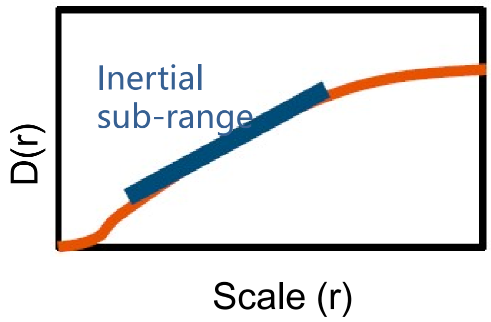
    $$D_{xy}(r) \equiv \overline{[x(r_0 + r) - x(r_0)][y(r_0 + r) - y(r_0)]}$$

    Kolmogorov “2/3 law” in inertial sub-range:

    $$D_x(r) = C_x^2 r^{2/3}$$

    $$D_{xy}(r) = C_{xy} r^{2/3}$$





→ **Structure parameters**

$$C_x^2 \equiv D_x(r) r^{-2/3}, \quad C_{xy} \equiv D_{xy}(r) r^{-2/3}$$

Theory of Scintillometry

1. Measured light intensity (I_{las}, I_{mws}) $\rightarrow$ Refactivity structure parameters $C_{n,las}^2$, $C_{n,mw}^2$, $C_{n,oms}$

$$\sigma_{lnI}^2 = 16\,\pi^2 k^2 \int_0^L d \int_0^\infty d\kappa\, \kappa\, \Phi_n(\kappa)\, sin^2\left(\frac{\kappa^2 x(L-x)}{2k_{las}L}\right)\left[2\frac{J_1(0.5\kappa Dx/L)}{0.5\kappa Dx/L}\right]^2 \cdot \left[2\frac{J_1(0.5\kappa D(1-x/L))}{0.5\kappa D(1-x/L)}\right]^2$$

$k = 2\pi/\lambda$ $\qquad$ $\phi_n = 0.033\, C_n^2 \kappa^{-11/3}$ $\qquad$ Diffraction $\qquad$ Aperture averaging

2. $C_{n,las}^2$, $C_{n,mws}^2$, $C_{n,oms}$ $\rightarrow$ Meteor. structure parameters (C_T^2, C_{Tq}, C_q^2)

$$C_n^2 = \frac{A_T^2}{\overline{T}^2} C_T^2 + 2\frac{A_T A_q}{\overline{T}\overline{q}} C_{Tq} + \frac{A_q^2}{\overline{q}^2} C_q^2$$

All A_T & A_q are functions of P, T, q, and λ

3. C_T^2, C_q^2 $\rightarrow$ Sensible & Latent heat fluxes (H, $L_v E$) with M_O Similarity

$$\frac{z^{2/3} C_T^2}{T_*^2} = f_T\left(\frac{Z}{L}\right) \qquad \frac{z^{2/3} C_q^2}{q_*^2} = f_q\left(\frac{Z}{L}\right) \quad \rightarrow \quad H = \rho C_p u_* T_*,\;\; L_v E = -\rho L_v u_* q_*$$

Scintillometer Types

Major scale parameters:

- Wave length λ. Aperture *D*.
- Path length *L*. The first Fresnel scale $F = \sqrt{\lambda L}$
- The larger of *D* & *F* determines effective turbulence scale

Type	λ	*D*	*L*	$F = \sqrt{\lambda L}$	Length scale in Turbulence	Parameter Sensitivity	Scintillometers
LAS	0.9 μm	≈15 cm	0.5 - 5 km	≈ 4 cm	$L_0 > D > F > l_0$	$C_n^2 \to C_T^2 \to H$ ↑ (u_*)	Kipp & Zonen LAS Scintec BLS450, 900
XLAS	0.9 μm	≈30 cm	5 - 10 km	≈ 10 cm			Kipp & Zonen XLAS Scintec BLS2000
SAS, DBLS	0.7 μm	2.5 mm	≈100 m	≈ 1 cm	$L_0 > F \geq D \approx l_0$	$l_0, C_n^2 \to \varepsilon, C_T^2 \to u_*, H$	Scintec SLS20, 40
MWS*	1.86-11 mm	30-40 cm	1 - 10 km	≈ 3-4 m	$L_0 > F > D > l_0$	$C_n^2 \to (C_T^2, C_q^2) \to H, LE$ ↑ (u_*)	CEH/RAL94, RPG-160

* MWSmust be used in combination with a LAS to determine C_q^2

EC & Scintillometers: Pros & Cons

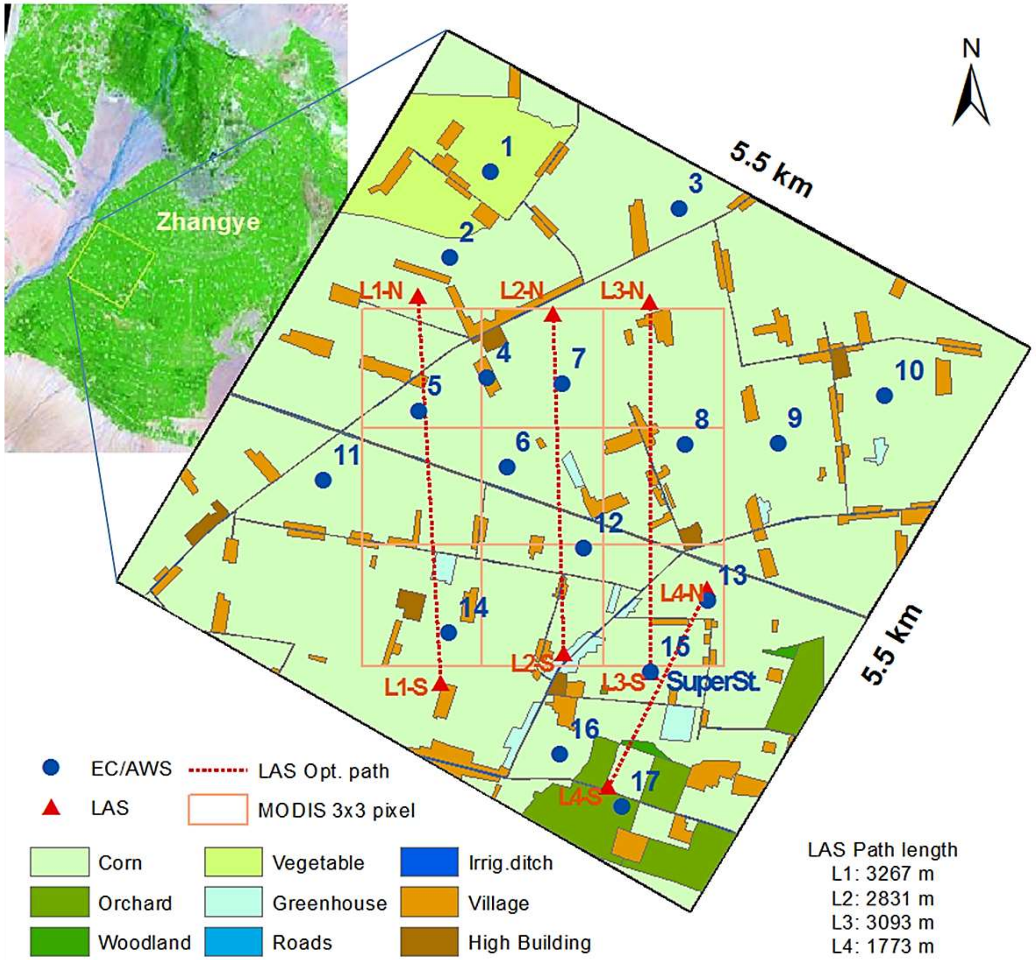
- EC is the only direct method in measuring flux, also, an accepted standard in calibrating other techniques.
- EC has limited by atmospheric status and sampling/averaging periods. Its surface representative is small (0.05~0.5 km^2).
- Scintillometry works mainly on 'one eddy scale' (F or D). It can measure statistically stable fluxes rapidly (<1min), also, area-averaged H (& λE) over heterogeneous terrain. Its surface representative can be 5~10 km^2.
- Scintillometry needs similarity relationships for fluxes. The uncertainty is larger. Some technique is still in development.
- Combining EC & Scintillometers can provides better area averaged fluxes, also, refined flux aggregation schemes.

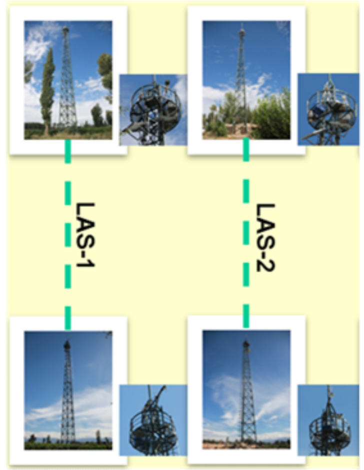
HiWATER flux matrix in Zhangye oasis, NW China, 2012

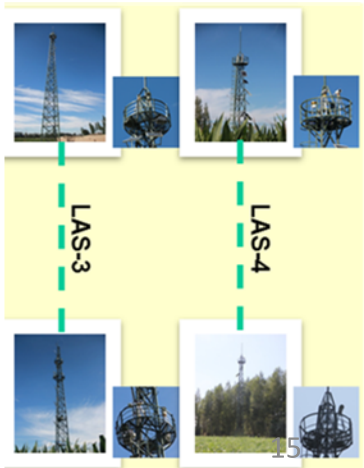
17 EC sites and 4 LAS paths in a 5 x 5 km^2 area

Super station

Other EC sites





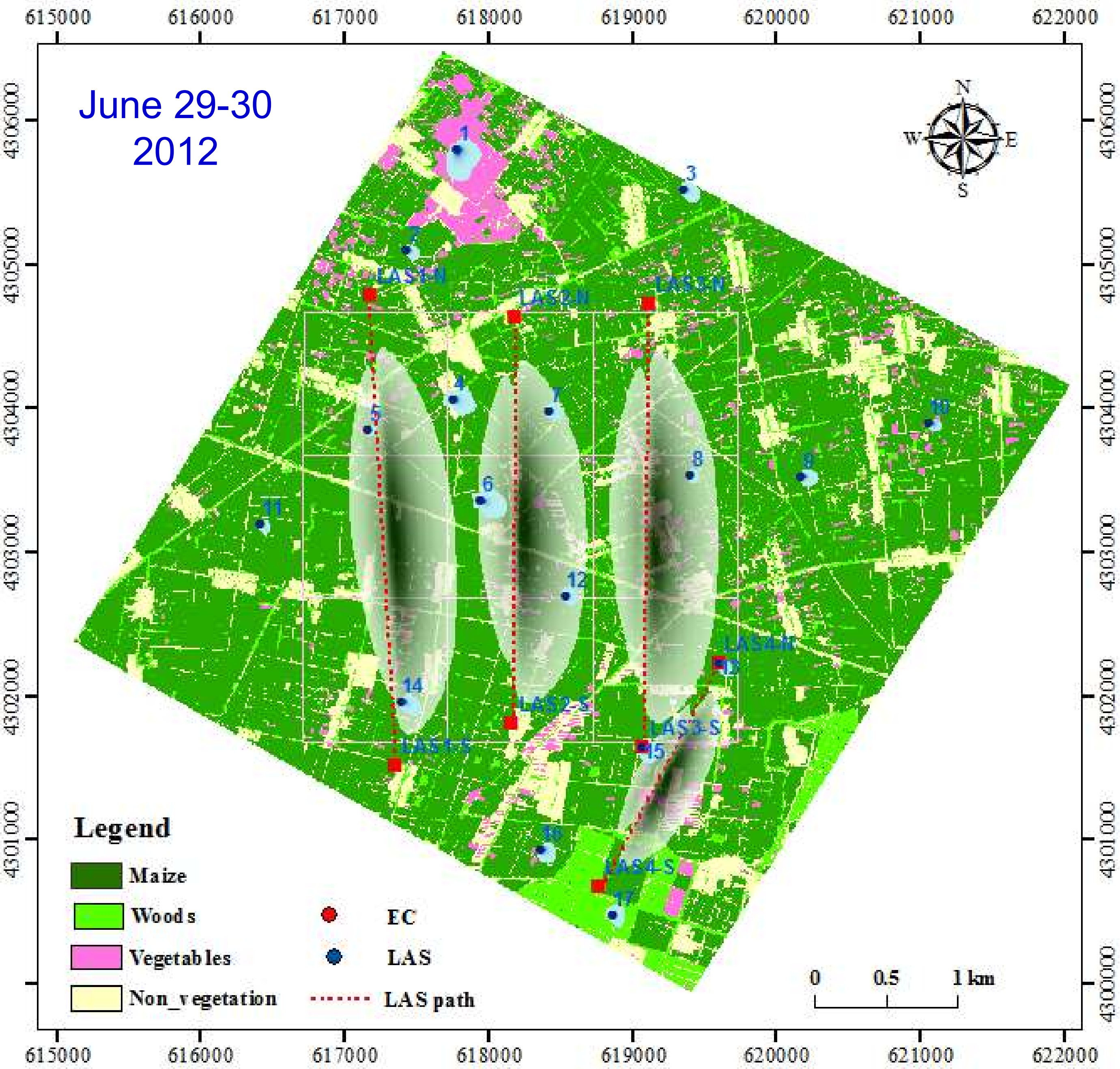


HiWATER Intensive Obs. Area

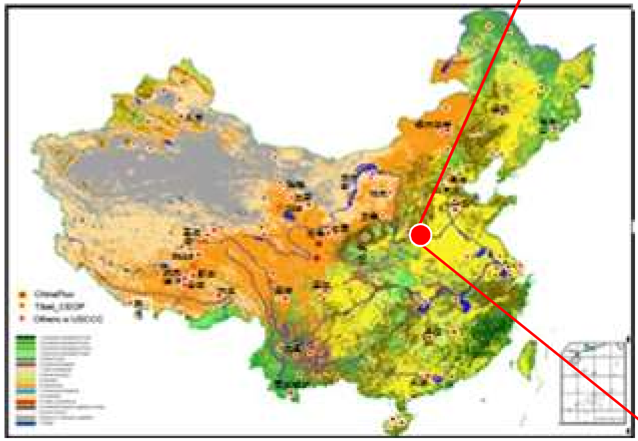
1) High res. Land-use map

2) Footprint calculations for ECs & LASs

3) A disintegrate/ integrate scheme developed to get ET for specific land-uses and for the whole area, which are used to validate remote sensing models.



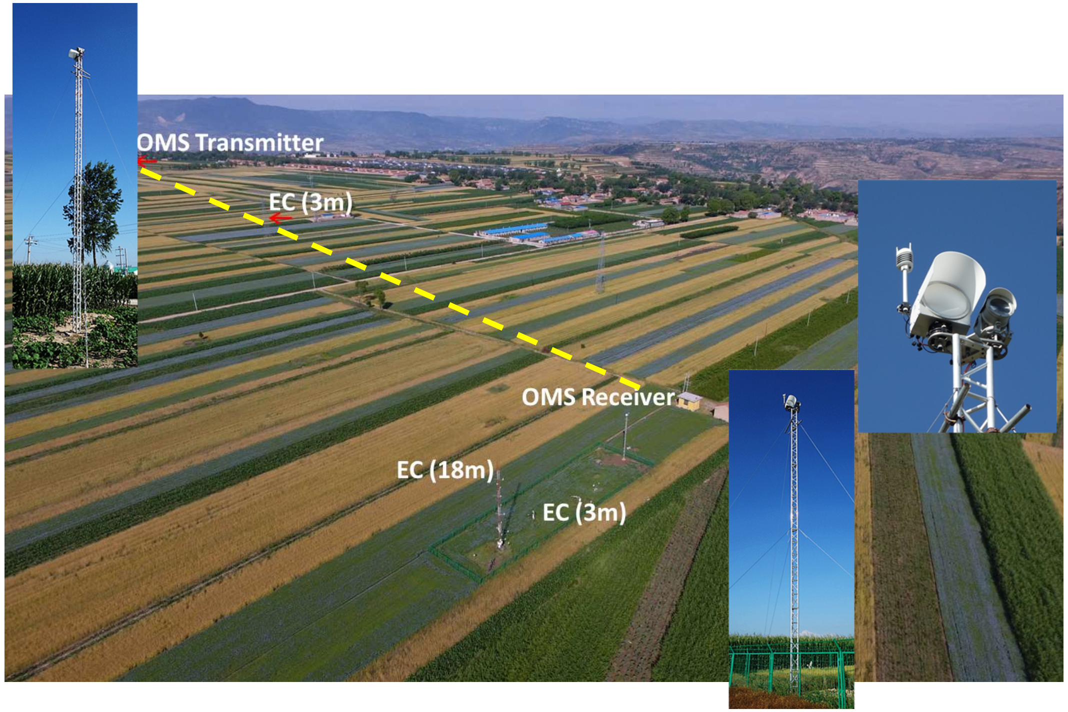
OMS in Xiaolangdi
Forest Ecological Station, CAF

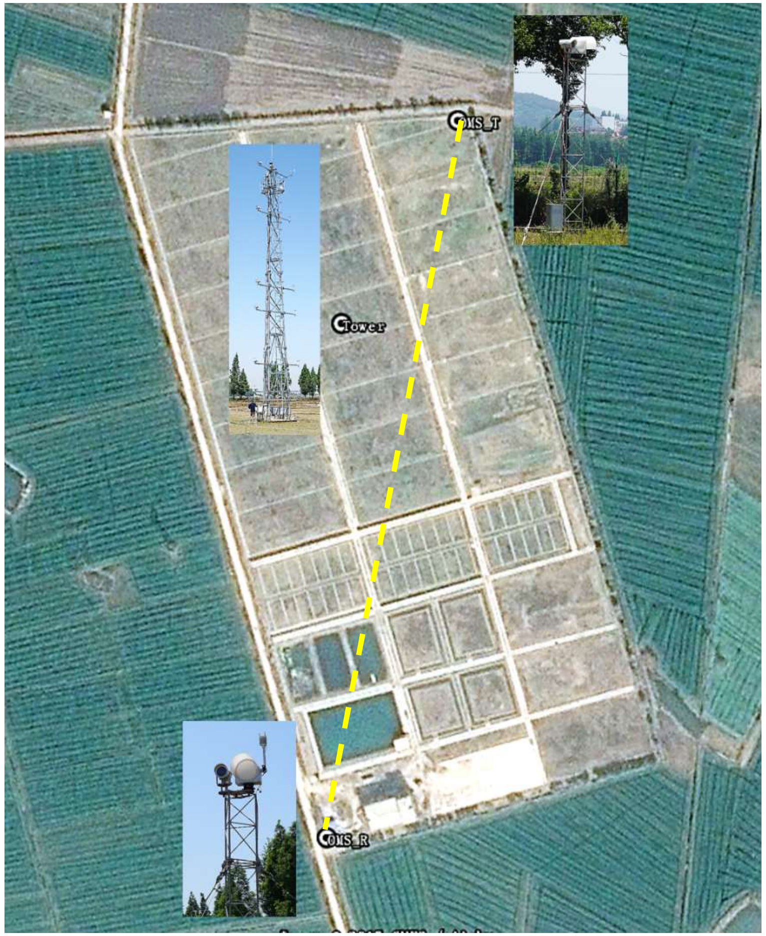


OMS in other two stations

Pingliang Flux Station on the Loess Plateau

Qujialing Station, Paddy Fields, Mid-South China

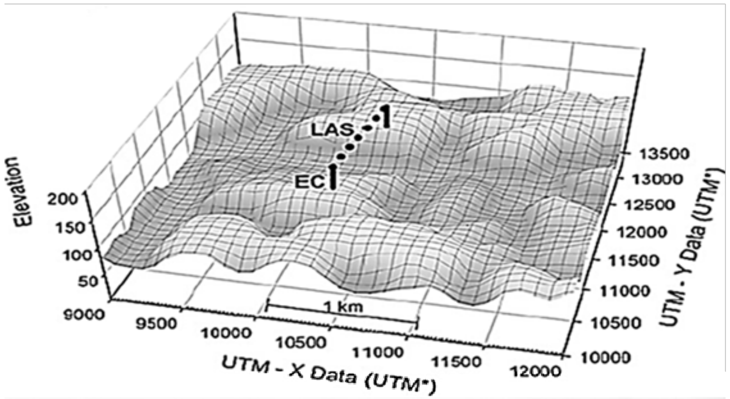


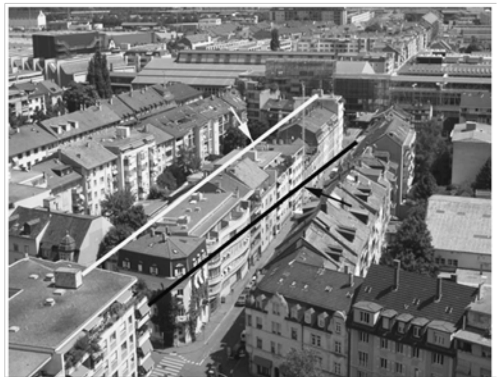


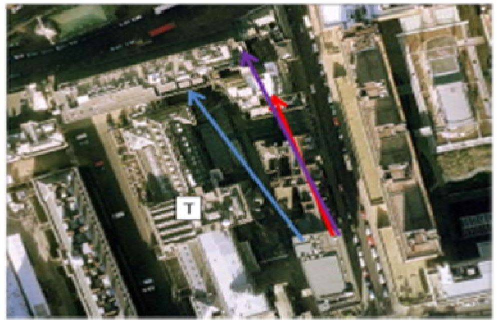
OMS: Height 12.5 m, Path length 1134 m

Application of scintillometers over Heterogeneous surfaces

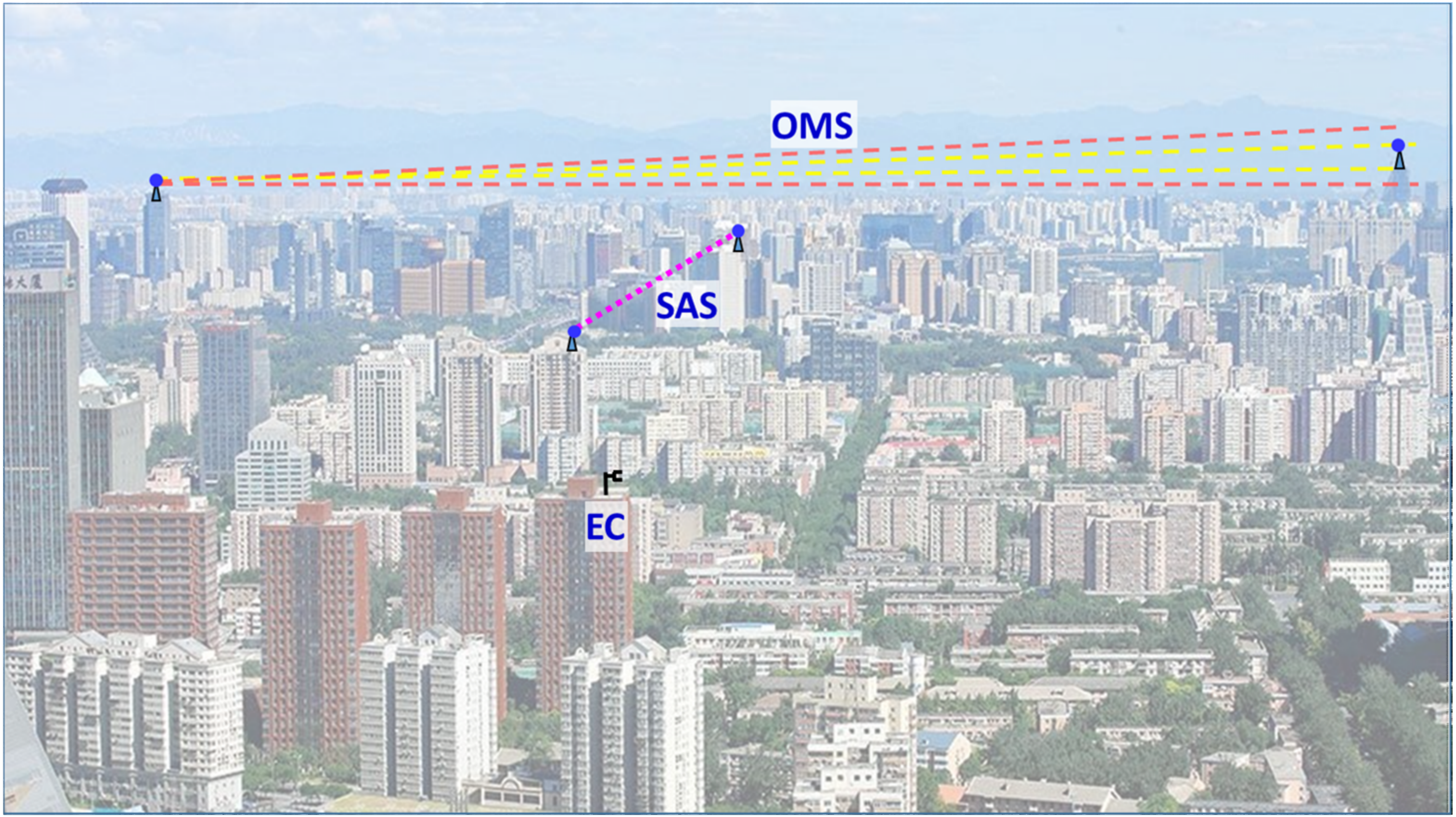
- Complex terrain
- Forest area (Amazon, China, Japan, etc.)
- Water surfaces (France, Mexico, S. Korea, etc.)
- Urban areas (Marseilles, London, Tokyo, etc.)



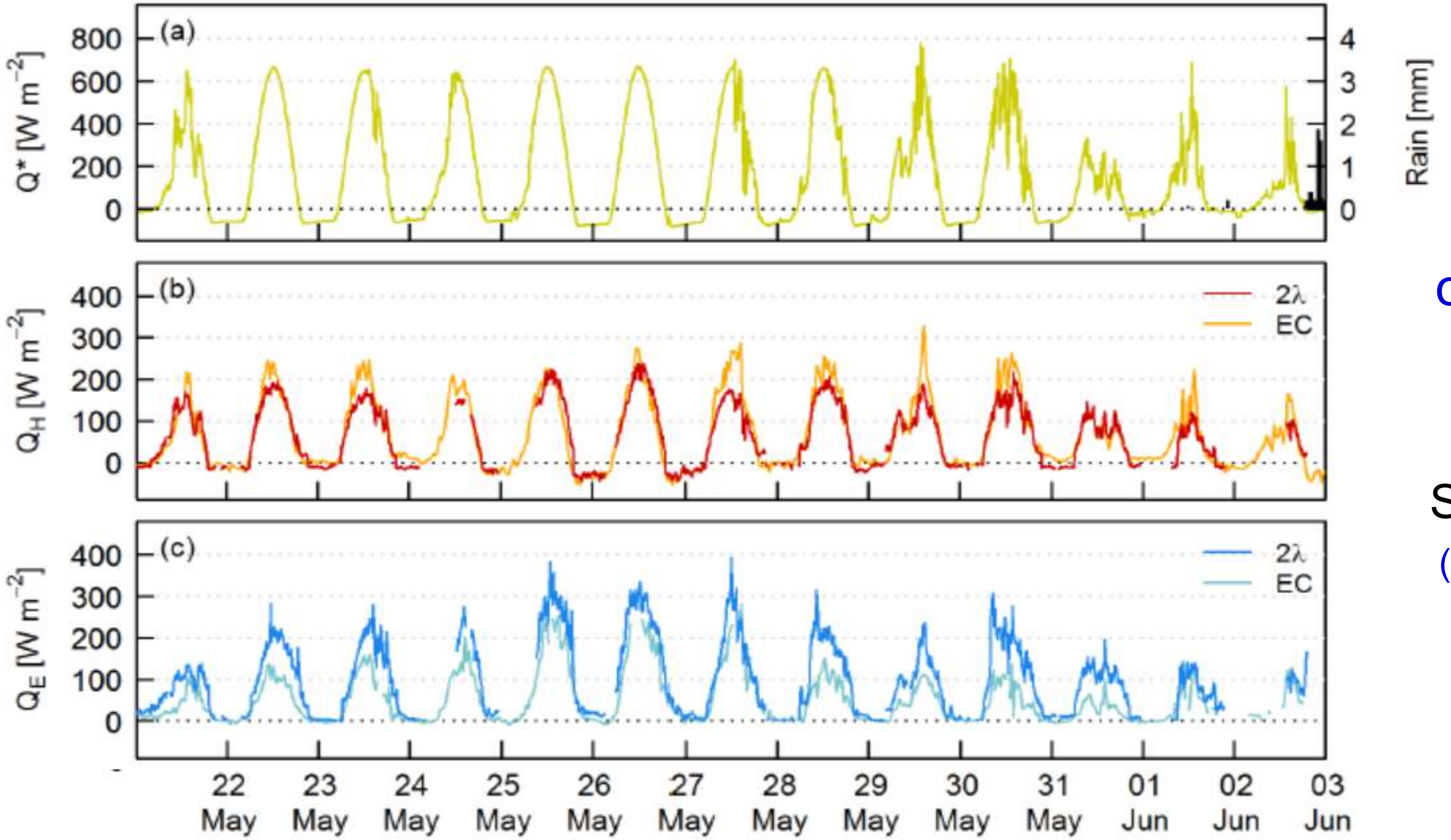




A conceptual configuration of observation over a complex urban area

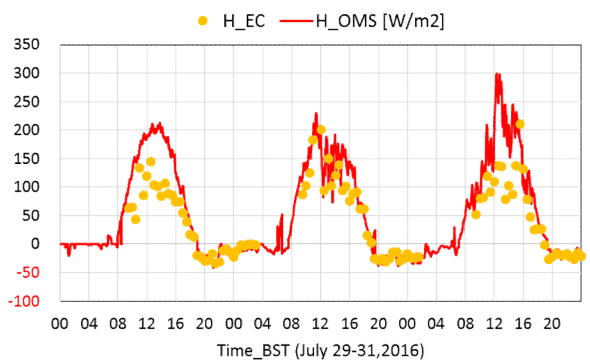


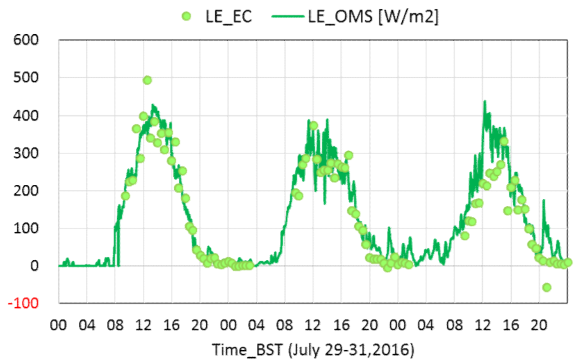
Comparison of OMS & EC



Swindon, Suburban, UK

(Ward et al. 2015)





Pingliang
Flat fields
China

Concluding Remarks 1

1. Observation of grid/pixel scale fluxes is essential for model predictions.
2. Last 20 years operation approved that scintillometry is an effective method to measure fluxes at 1-10 km scale. In both practical & theory, scintillometry offers advantages. It is to be a complementary technique for EC in flux networks.
3. Scintillometry is a valuable technique especially for flux observations in complex environment. As general consensus, reasonable fluxes are obtained by using scintillometers in urban area. M-O similarity theory appears to be applicable in these areas; its related issues are not more problematic than homogeneous surfaces;

(H Ward 2017)

Concluding Remarks 2

4. Footprint modeling is a valuable tool for relating LAS/MWS measurements to surface characteristics & area-integrated fluxes.
5. Besides fluxes, scintillometry can also measure crosswind, rainfall, visibility, and estimate CO_2 & other scalar fluxes.
6. Scintillometry data is particularly useful to evaluate model output and satellite products. It should be a priority to create new links between scintillometry and models, remote sensing, & airborne data.
7. Concerning current rate of progress in sensor and data processing techniques, the next 20 years offers great potential for advances in scintillometry.

Thank You !

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https://www.researchgate.net/project/Scintillometry

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Scintillometry

Jiemin Wang · Henk de Bruin

Goal: Measurement of sensible and latent fluxes in the scale of 1-10 kilometers

Scintillometry: a review

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Abstract

A book is in preparation:

Application of Scintillometry in Environmental Sciences

A review of renaissance of scintillometry

By H.A.R. de Bruin and Jiemin Wang

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