Laboratory of WIND ENERGY & TURBULENCE
THE UNIVERSITY OF UTAH

A revised representation of atmospheric surface layer processes over perturbed surfaces and the need for the next generation of field experiments.

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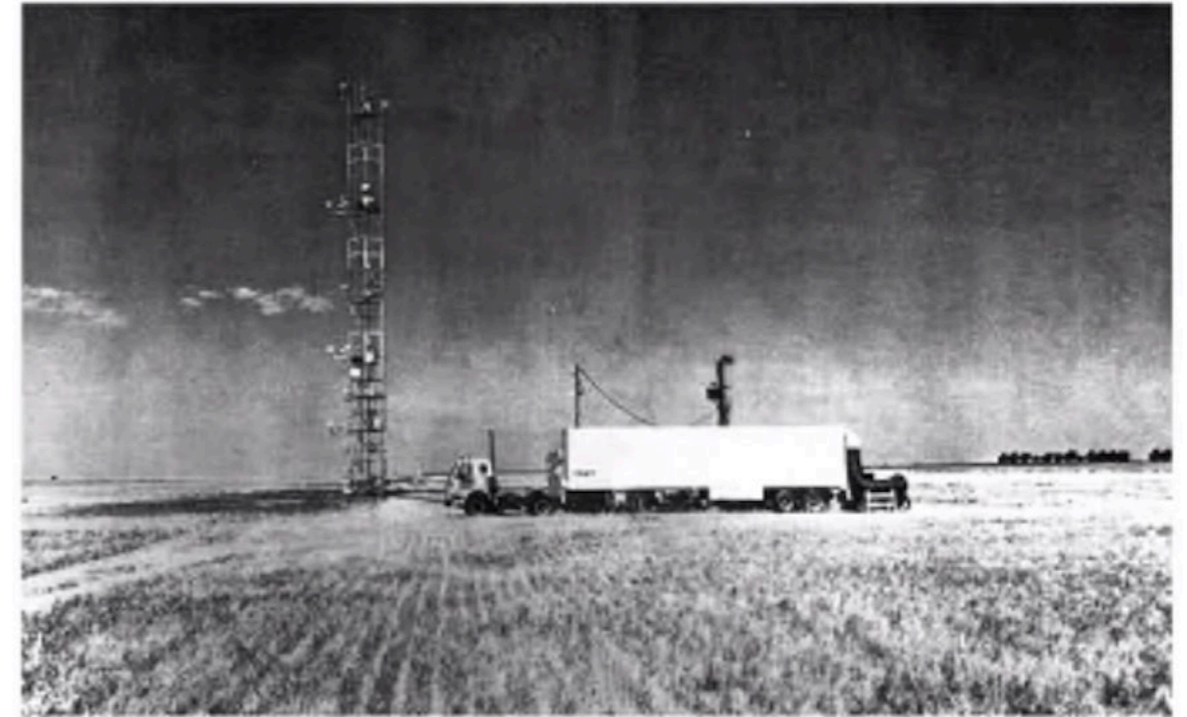
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Near the surface, in classic ABL theory it is commonly hypothesised

- Stationarity,

- Horizontal homogeneity,

- No subsidence,

➡️ **Simplification of the mean equations**

Kansas 1969 Experiments

Example: Scalar transport equation

$$\cancel{\frac{\partial \overline{C}}{\partial t}} + \overline{u}_j \cancel{\frac{\partial \overline{C}}{\partial x_j}} = -\frac{\partial \overline{u_j' C'}}{\partial x_j} + \overline{S}_c$$

Homogenous & flat world

$$\frac{\partial \overline{w'C'}}{\partial z} \approx \overline{S}_c \quad \longrightarrow \quad \overline{w'C'}(z) \approx \int_0^z \overline{S}_c \, dz + G$$

Embedded in these, **it is also assumed** that:

- Turbulence is locally generated,

- The vertical diretion (Z) is the only important one,

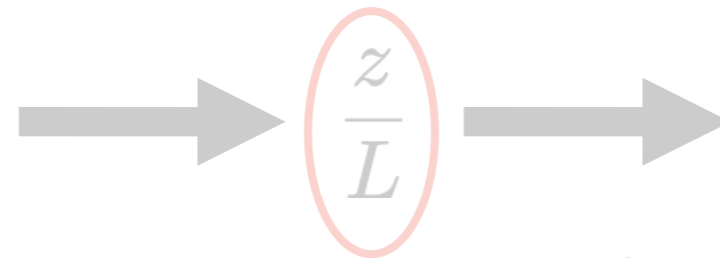- The energy containing eddies scale with distance from the world.

Single Tower Measurements should be <u>JUST FINE</u>!

Monin-Obukhov 1954 similarity theory:

(only 1 non-dimensional param.)

where, $\begin{cases} u_* \\ (\overline{w'\theta'_v})_s \\ \beta = g/\overline{\theta}_v \\ z \end{cases}$ $\Longrightarrow$ $\left(\dfrac{z}{L} \right)$ $\Longrightarrow$ such that $\boxed{\dfrac{\overline{x}}{x_*} = \Phi\left(\dfrac{z}{L}\right)}$

with: $L = \dfrac{-u_*^3}{\kappa\beta\,(\overline{w'\theta'_v})}$

Summary of the classical MOST scaling relations
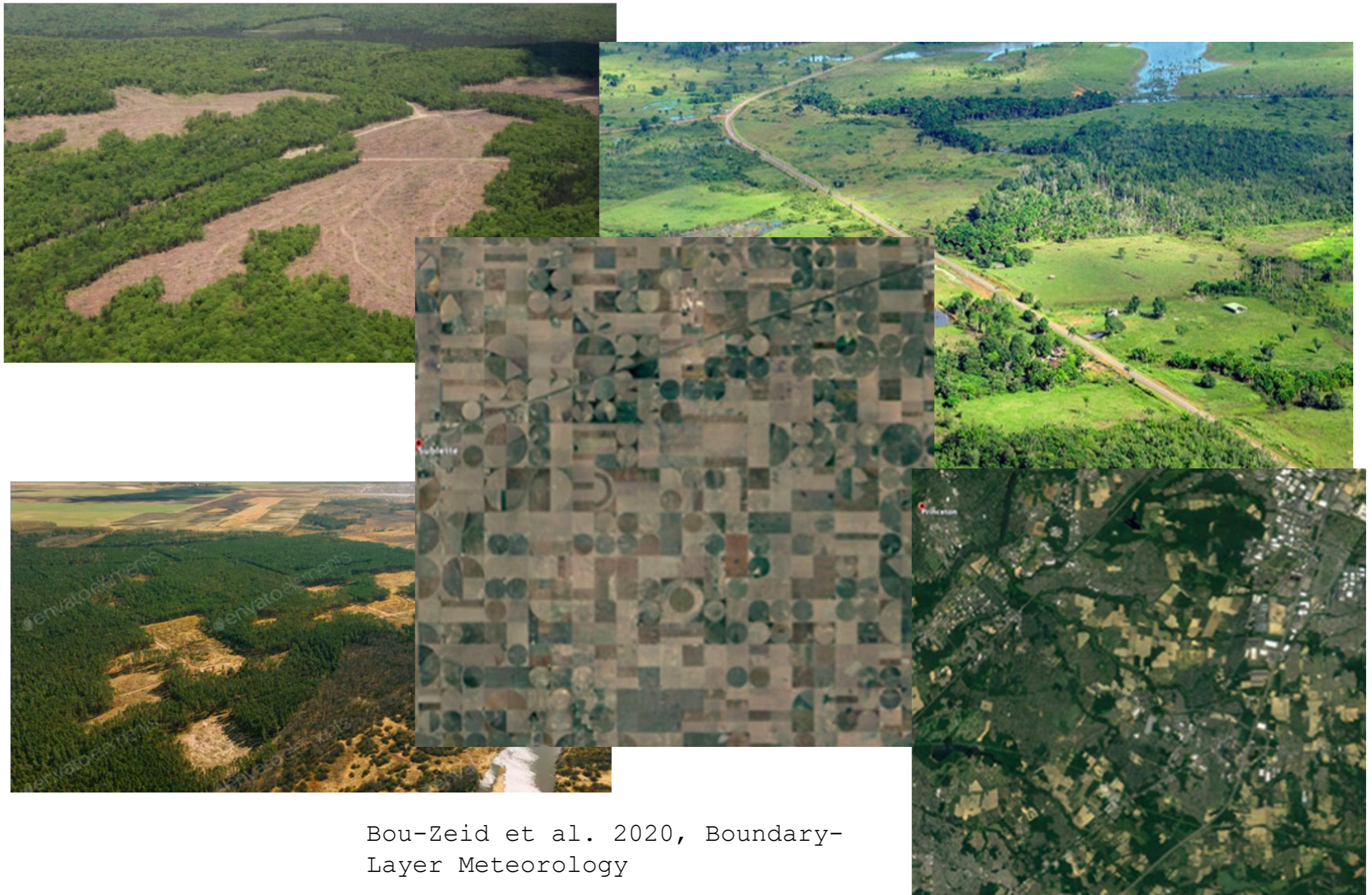

Kaimal & Finnigan 1994.
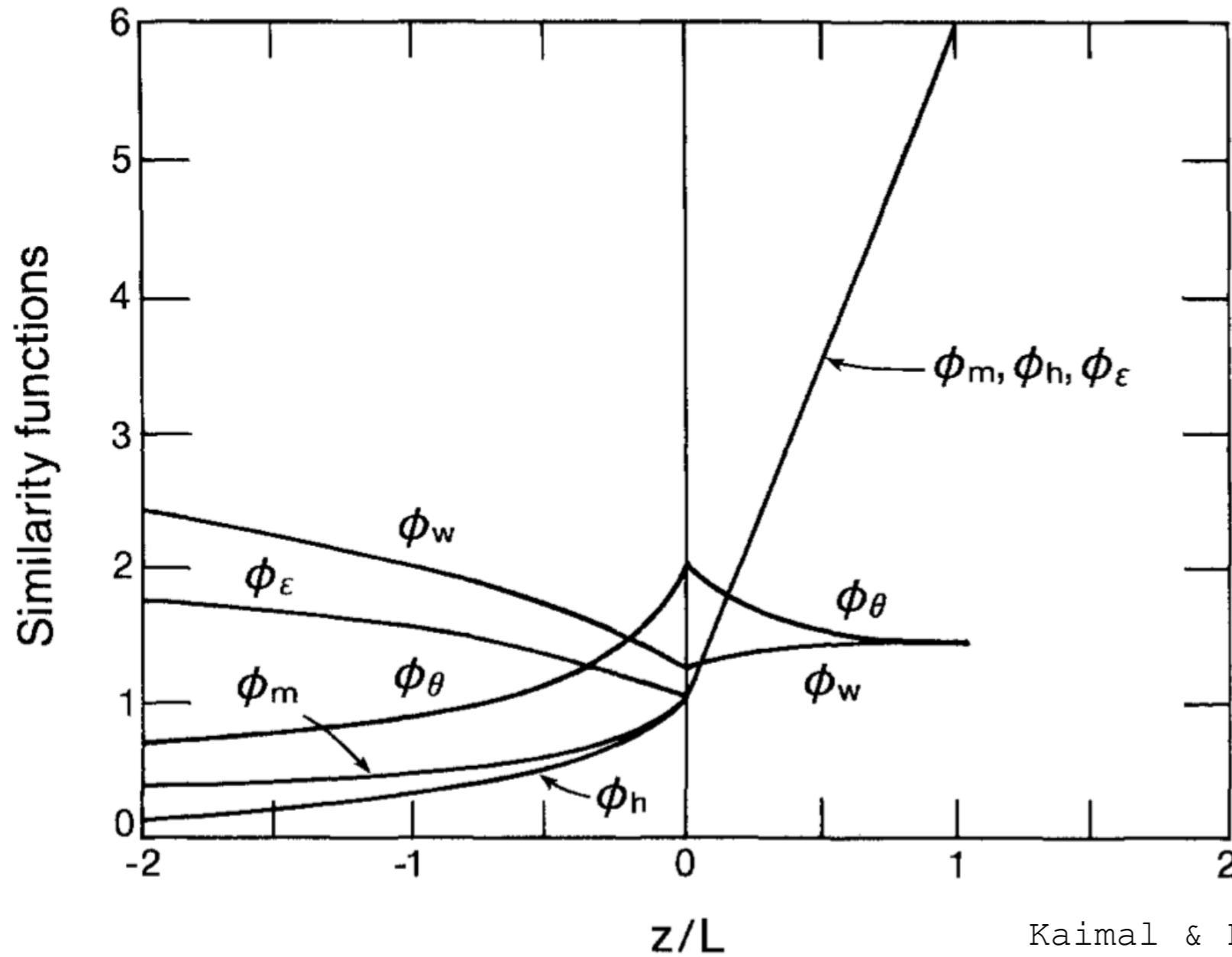
These relations are embedded in ESMs of all resolutions in one way or another!

But what happens in the case of ASL flows over Perturbed Surfaces where other length scales (besides "Z") might also matter ?
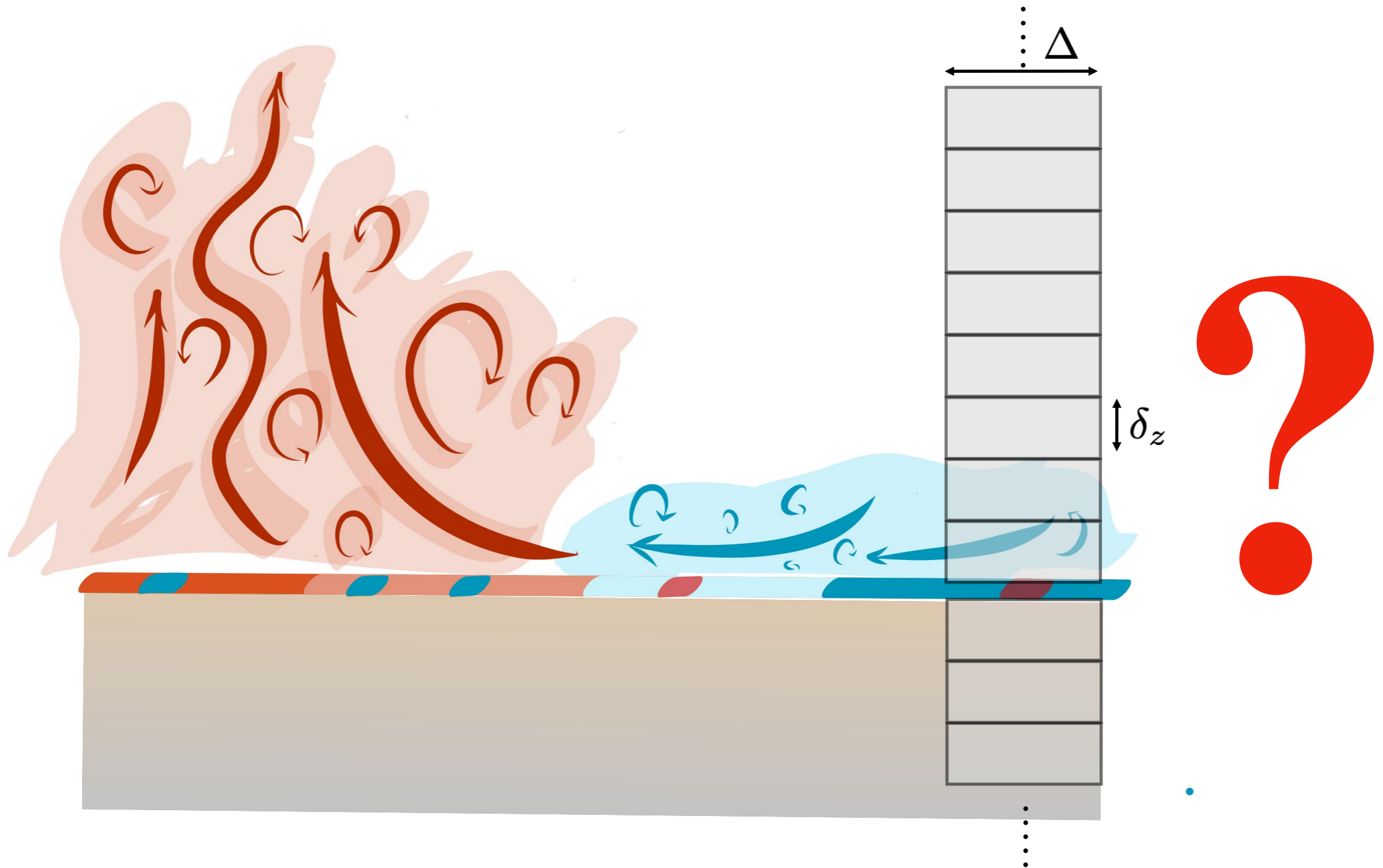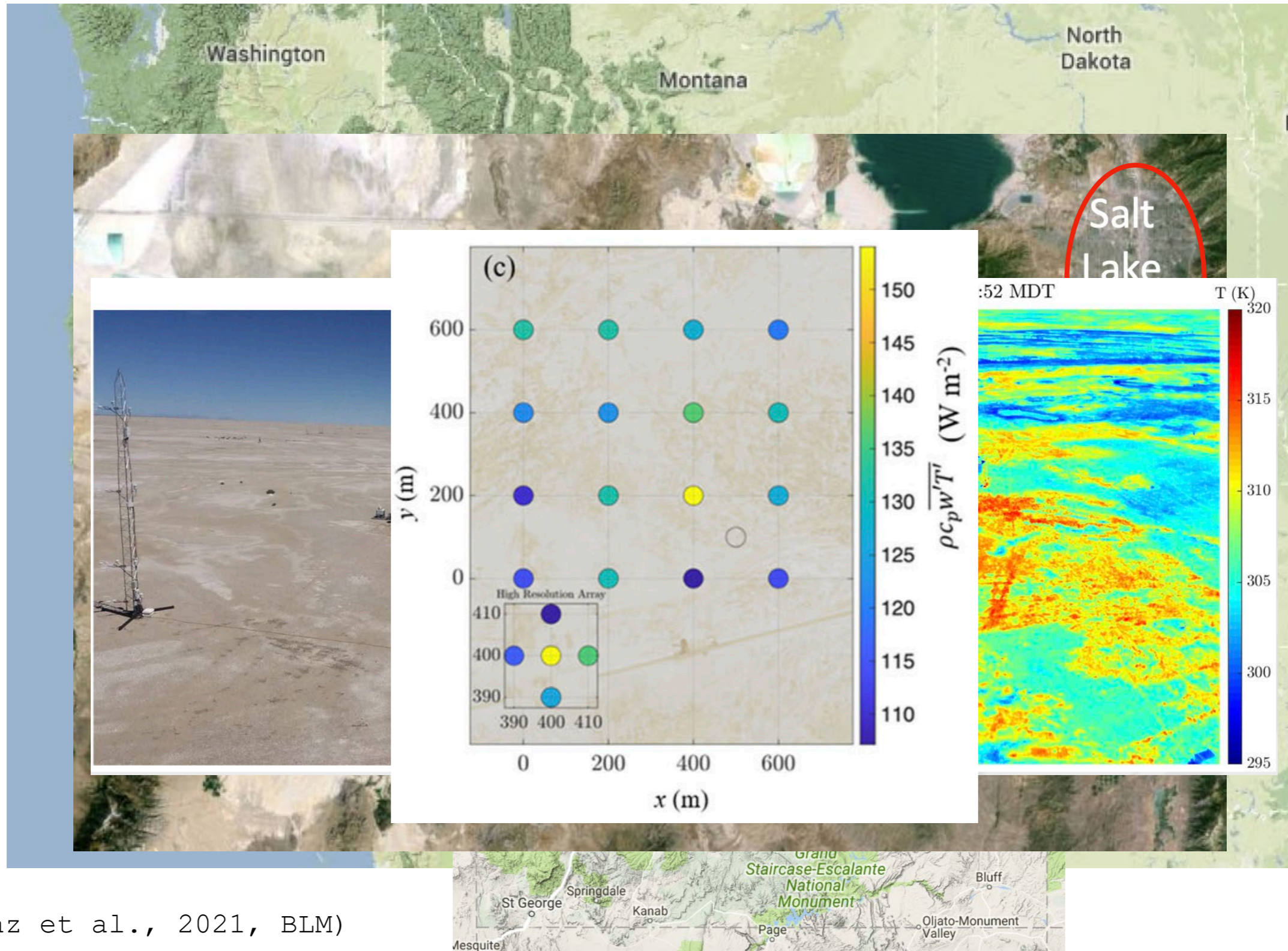
Land Surface Heterogeneity is omnipresent!

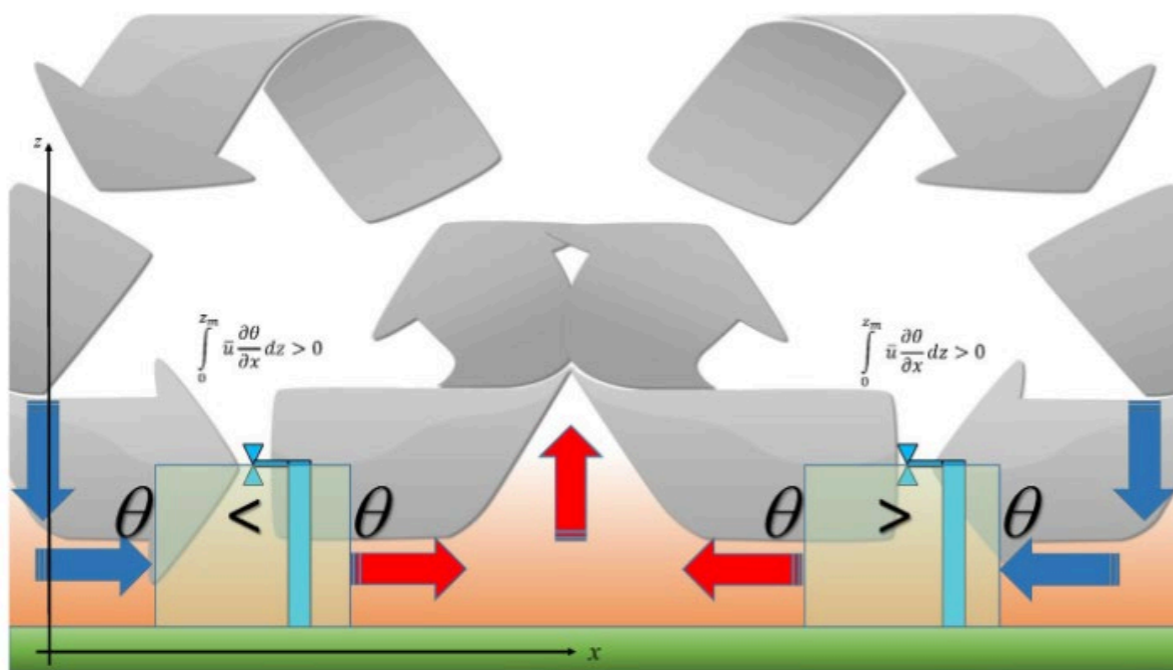Bou-Zeid et al. 2020, Boundary-Layer Meteorology

Even in the most "CANONICAL" sites !!
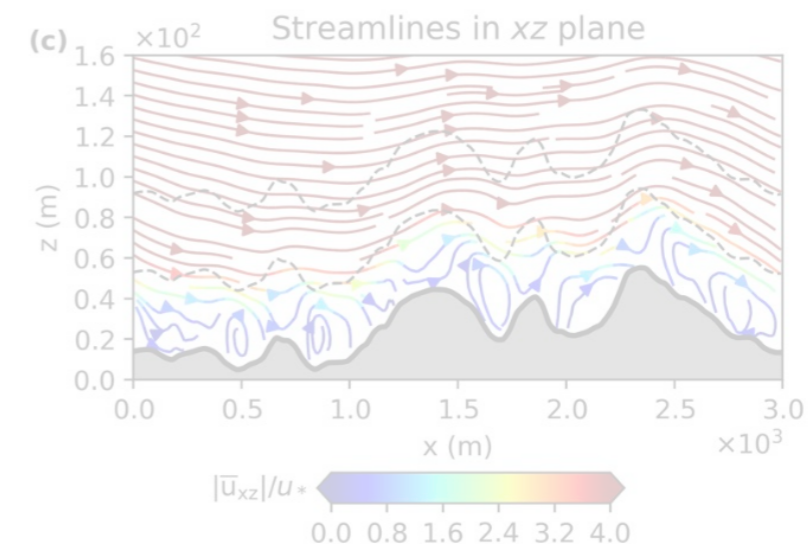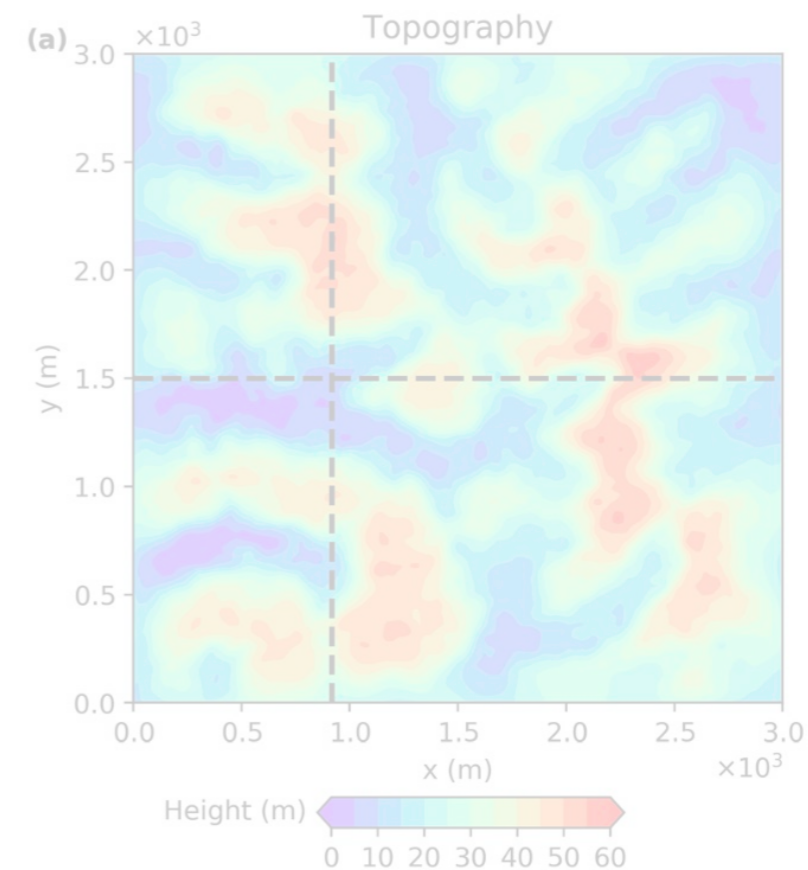

(Margairaz et al., 2021, BLM)

Example Effects of this heterogeneity:

(a) Effect of Secondary Circulations

$$\int_0^{z_m} \bar{u}\frac{\partial\theta}{\partial x}dz > 0 \qquad \int_0^{z_m} \bar{u}\frac{\partial\theta}{\partial x}dz > 0$$

$\theta < \theta \qquad \theta > \theta$

Mauder et al., BLM, 2020.

(b) Pressure perturbations induced transport in complex terrain

(a) Topography

Height (m)
0 10 20 30 40 50 60

(c) Streamlines in *xz* plane

$|\bar{u}_{xz}|/u_*$
0.0 0.8 1.6 2.4 3.2 4.0

Chen et al., JGR Atmospheres, 2020.

(c) … addition of other dominant length scales:

- **Mixing Layer height** (z_i),
- **Low-level jet** (z_j),
- **Heterogeneity scale**

**Therefore,** in most of these "perturbed" surface cases:

1. All assumptions embedded in MOST are violated, and this breaks down. Alternatives are needed for models and experiments!

2. Non-local advective transport processes are generated and must be accounted. These are currently neglected.

To help overcoming these issues we are investigating 2 approaches:

1. **Proposed Turbulence Anisotropy** as an additional non-dimensional term that enables generalizing MOST:

$$\frac{\overline{x}}{x_*} = \Phi\left(\frac{z}{L}, y_B\right)$$
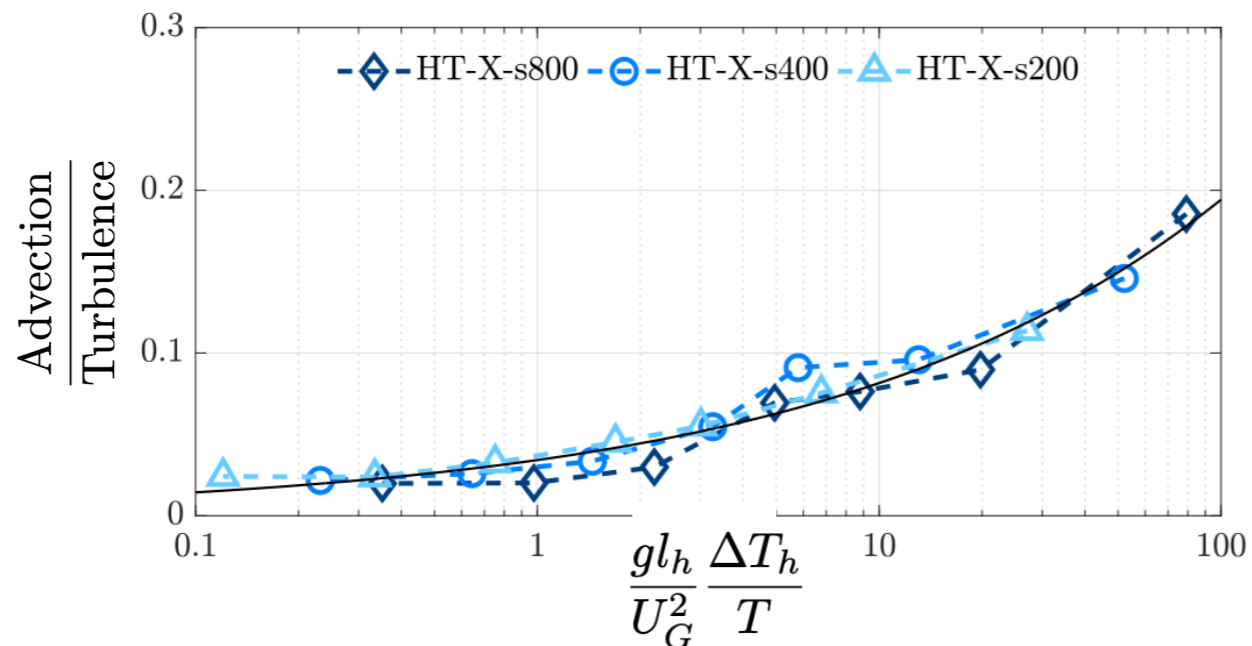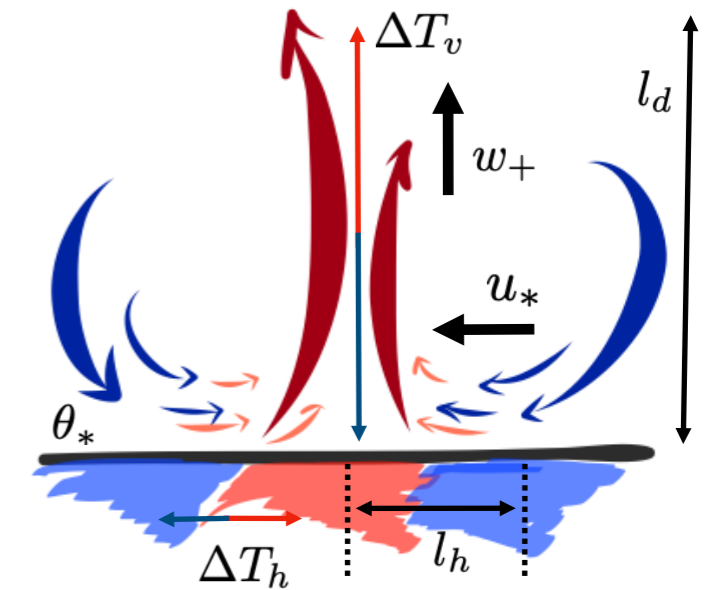
(Stiperski & Calaf, 2023, PRL)
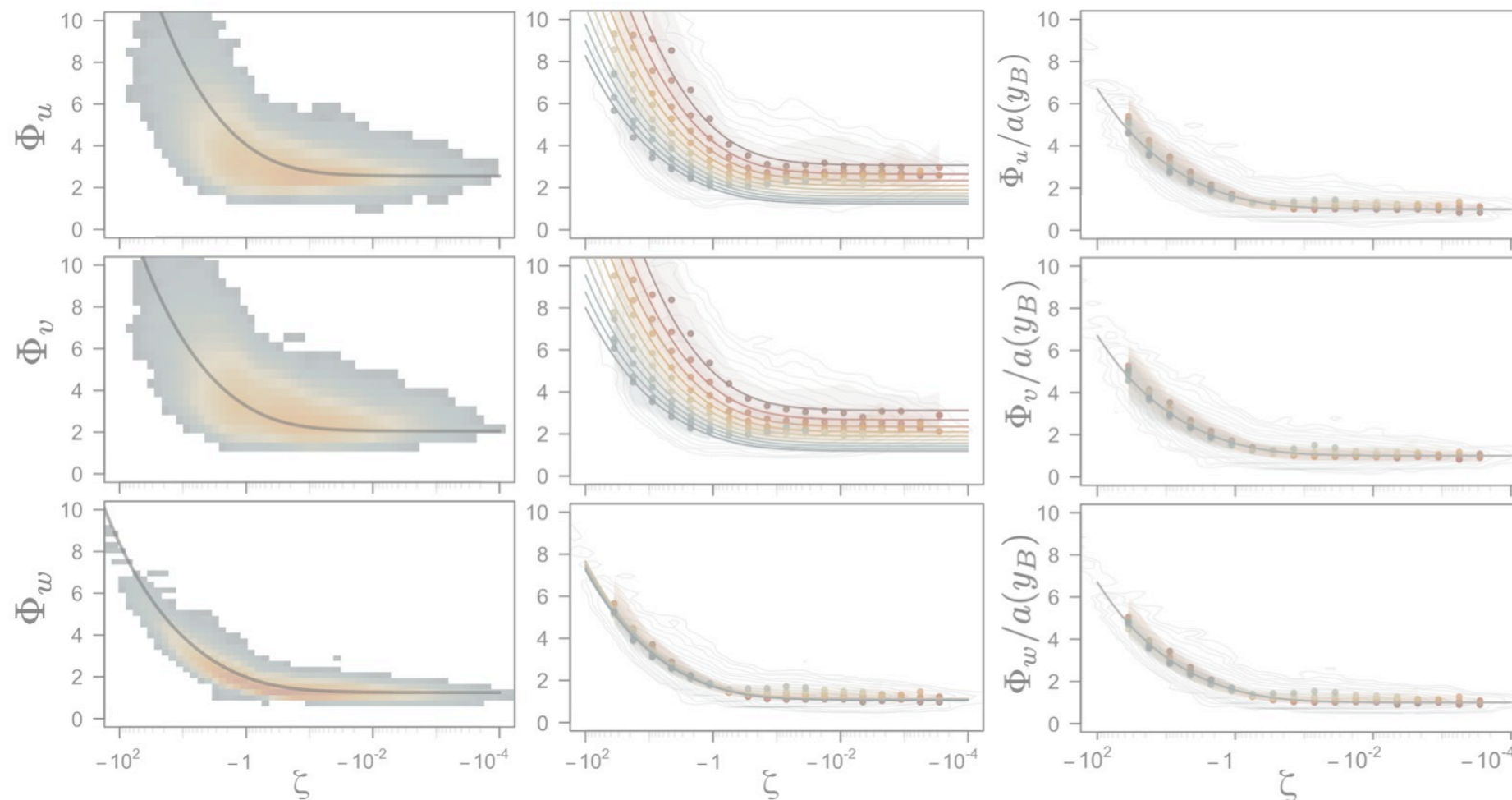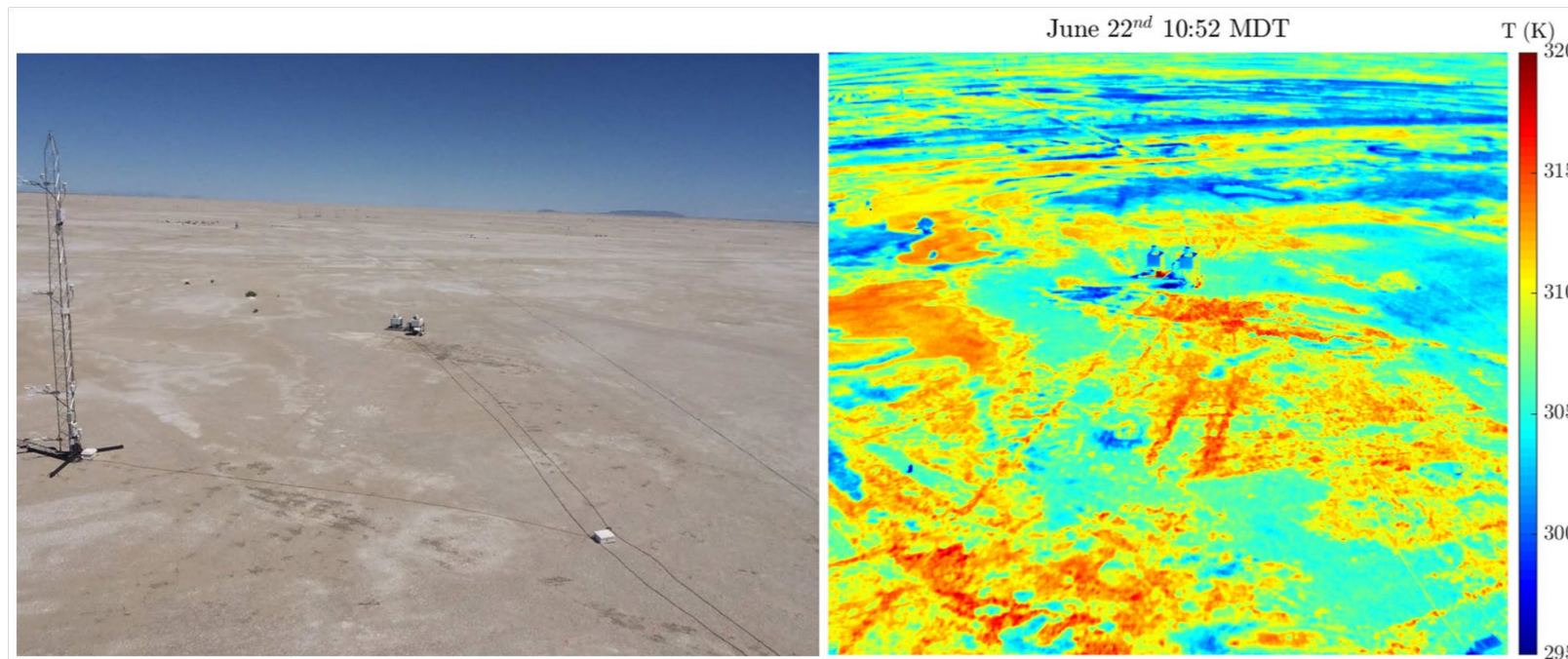

Data from the CABAUW, CASES-99, AHATS, METCRAX, iBOX, T-Rex, MATERHORN projects.

➡ Needs to investigate the effect of numerical resolution and filtering.

2. **Definition of a Heterogeneity parameter** that facilitates parametrizing the effect of Advection:

$$\frac{\text{Advection}}{\text{Turbulence}} \sim \left(\frac{g l_h}{w_+^2} \frac{\Delta T_h}{T} \right) \left(\frac{w_+}{u_*} \right)$$


(Margairaz et al., 2020a,b; BLM)

To test these and other new concepts we need "Next Gen" field experiments!

- Field experiments that go beyond single point measurements, and look more like LES Control Volumes,…

- Field experiments that allow us to compute the differential equations for Mass, Heat, and Momentum

- **Field experiments that we can use to test hypotheses/concepts developed first through "idealized" LES studies and then TESTED in real conditions**

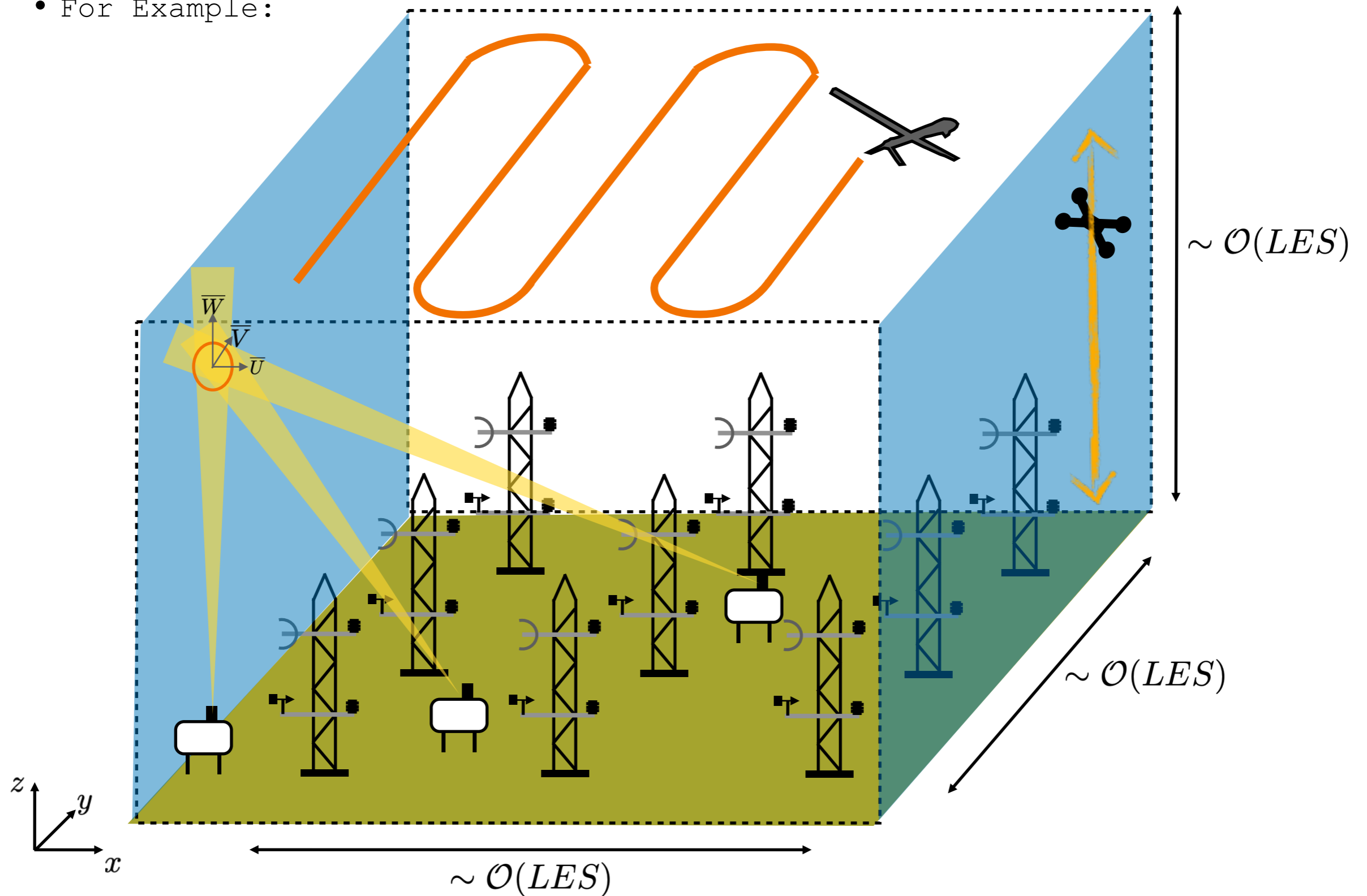- Field experiments that are not only designed to try to test/validate numerical simulations.

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- For Example:

$\sim \mathcal{O}(LES)$

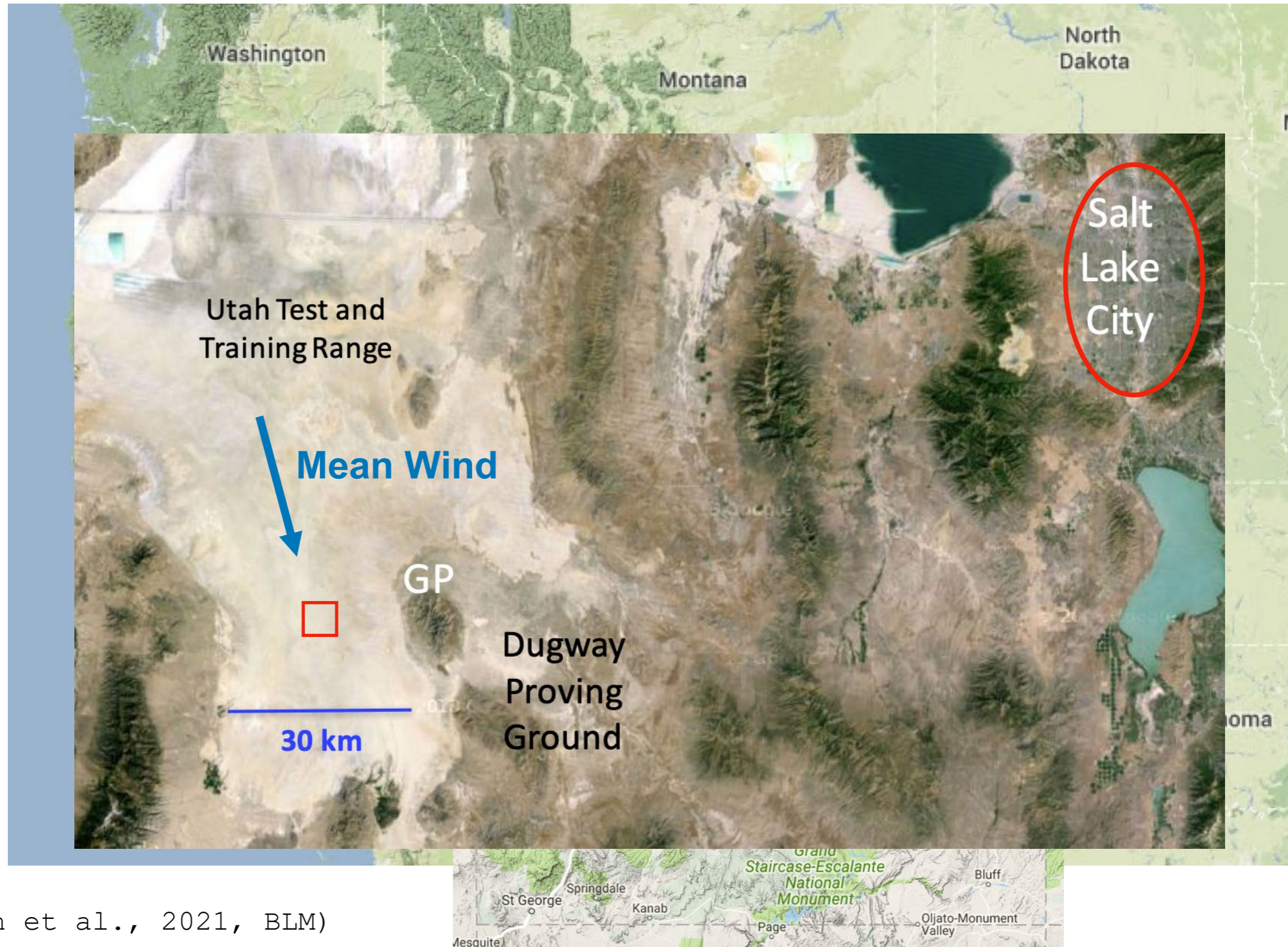$\sim \mathcal{O}(LES)$

z

y

x
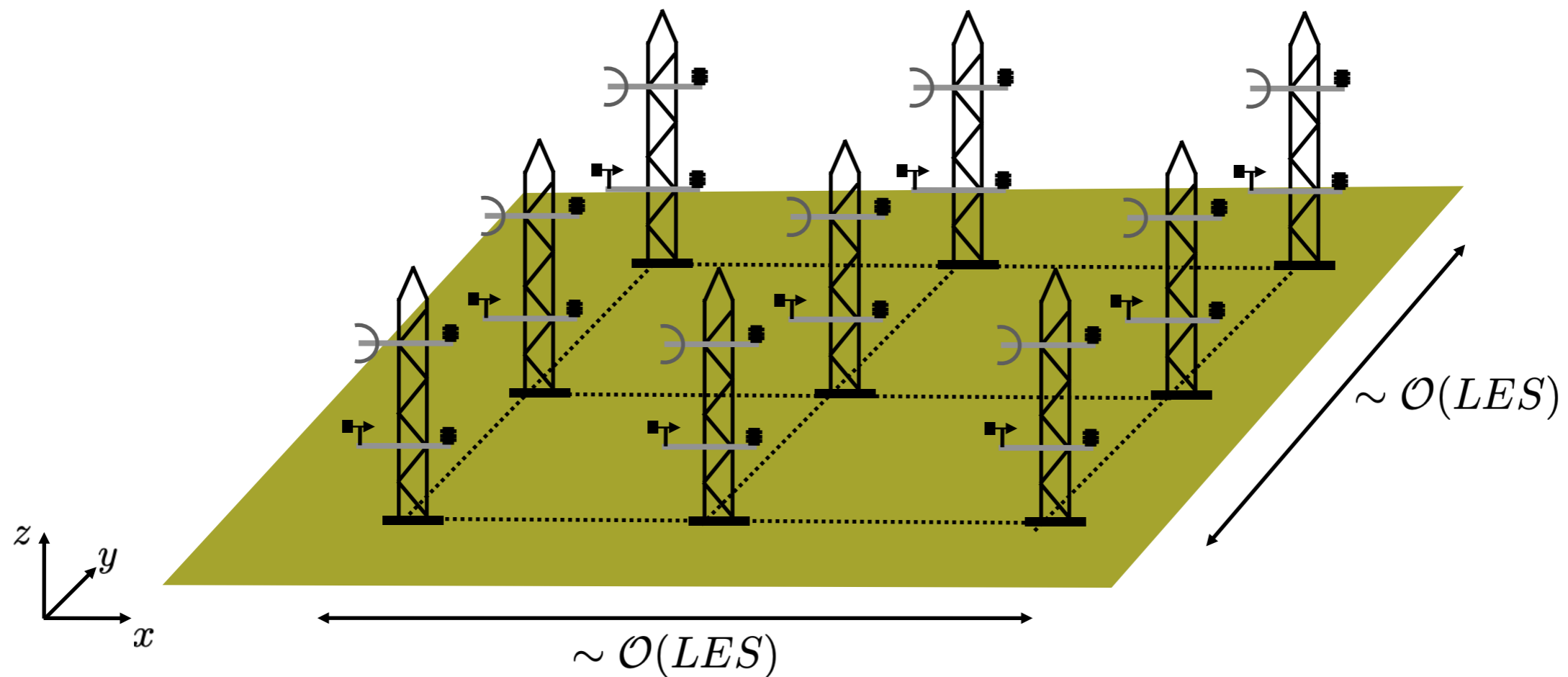
To test these and other new concepts we need "Next Gen" field experiments!

- For Example:

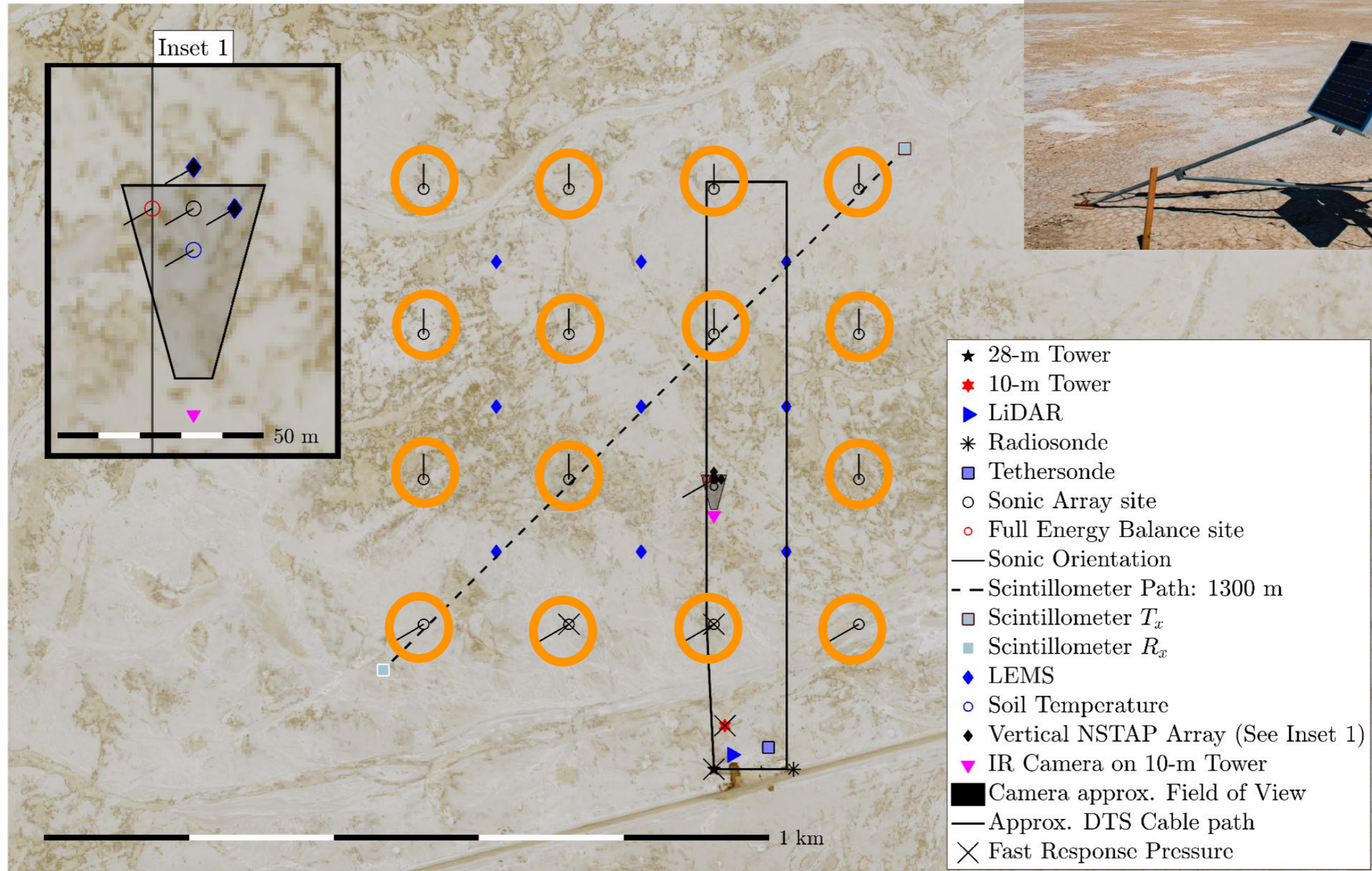# To illustrate that this is not such a CRAZY idea,…

We developed the Idealized Planar array study for Quanitfying Surface heterogeneity (IPAQS),…

(Morrison et al., 2021, BLM)

IPAQS 2018/2019

IPAQS18 Instrumentation Locations

Inset 1

50 m

1 km

★ 28-m Tower
✶ 10-m Tower
▶ LiDAR
✳ Radiosonde
◾ Tethersonde
○ Sonic Array site
○ Full Energy Balance site
— Sonic Orientation
- - Scintillometer Path: 1300 m
▫ Scintillometer T_x
▪ Scintillometer R_x
◆ LEMS
○ Soil Temperature
◆ Vertical NSTAP Array (See Inset 1)
▼ IR Camera on 10-m Tower
■ Camera approx. Field of View
— Approx. DTS Cable path
✕ Fast Response Pressure

Example results: Closure of the surface energy budget (SEB) during fair weather days.

The shading indicates the residual:

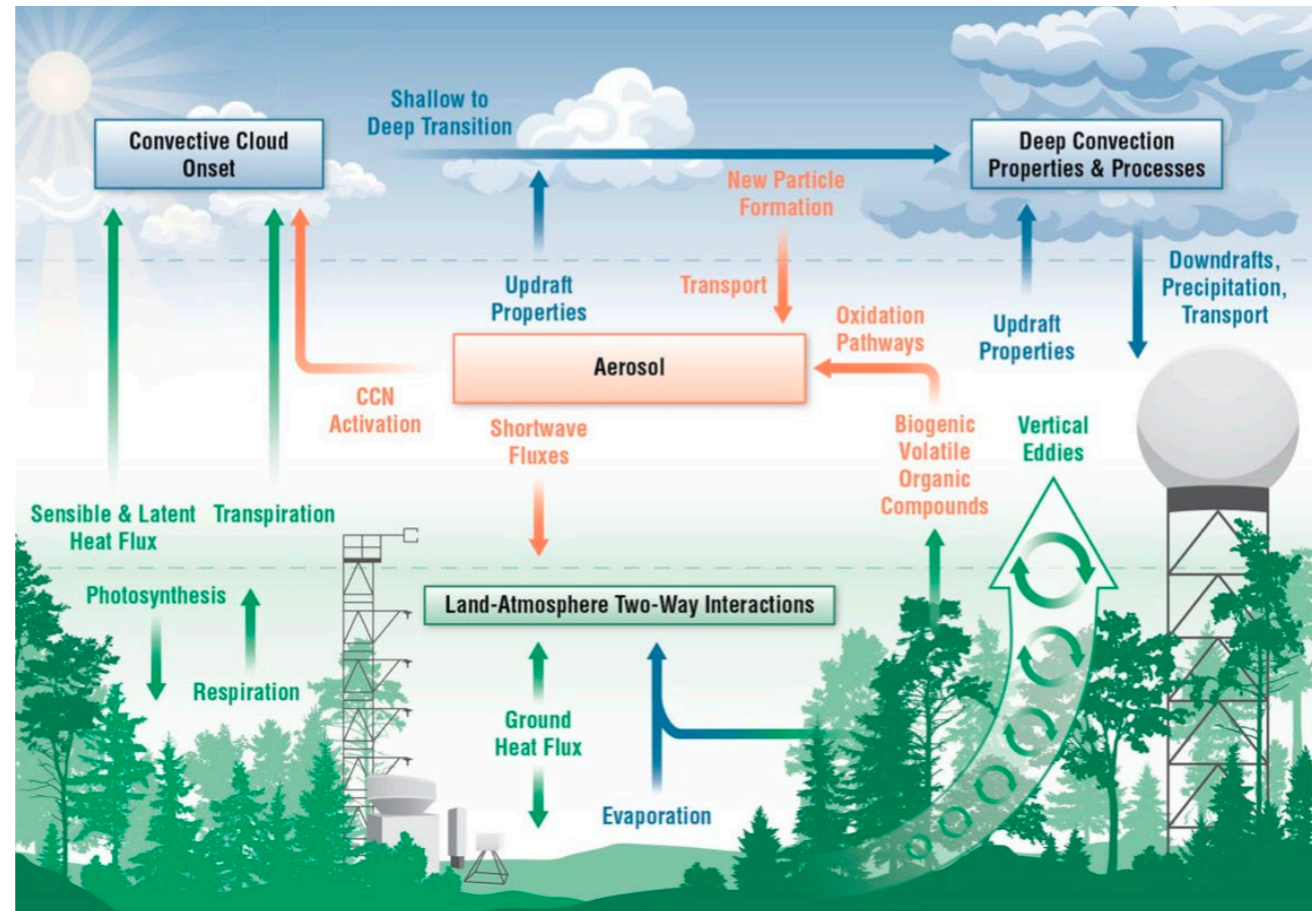$\blacksquare$ Residual $\leq 5\%$
$\blacksquare$ $5\% <$ Residual $\leq 15\%$
$\blacksquare$ Residual $> 15\%$
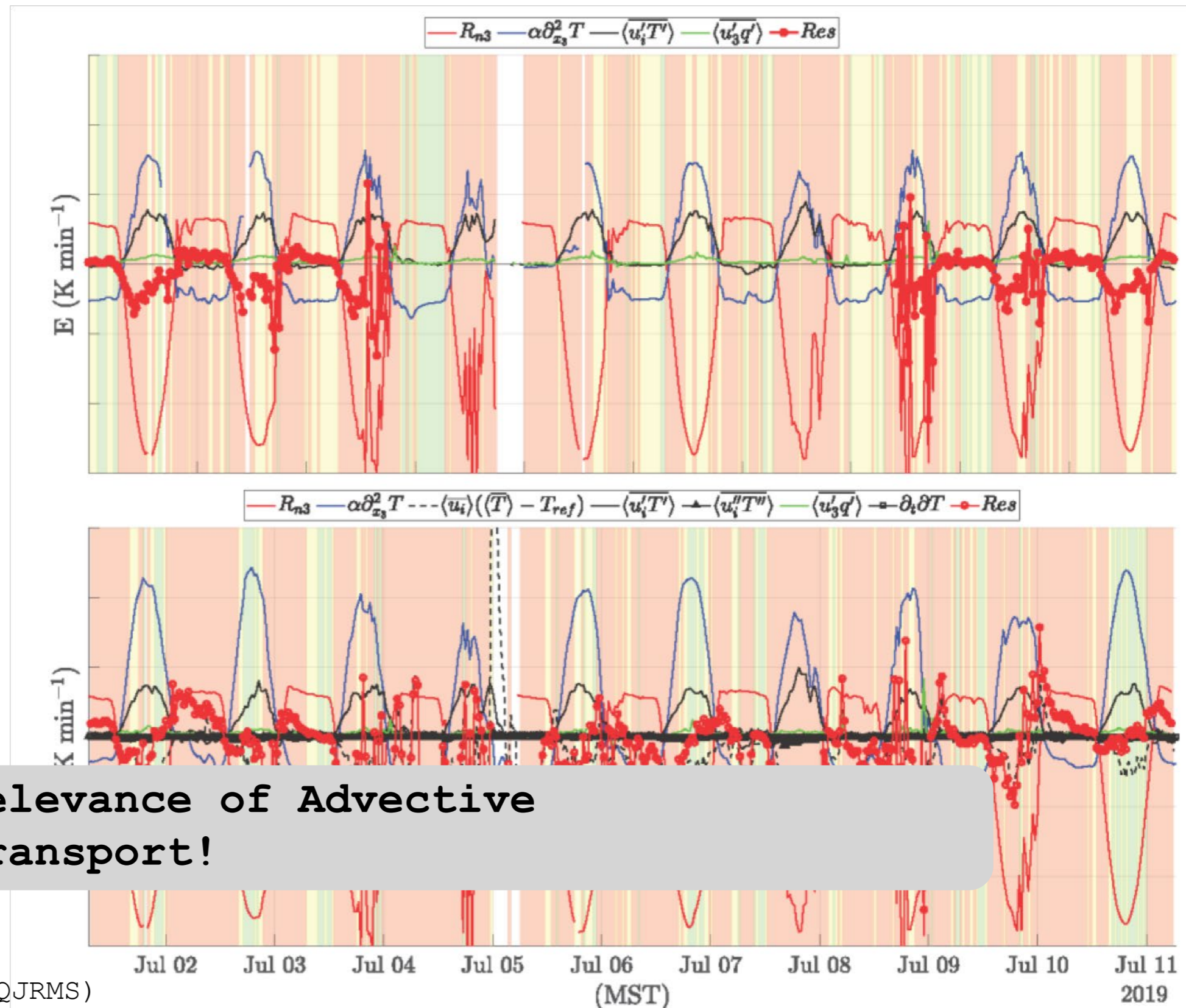
- **Relevance of Advective transport!**

(Morrison et al., 2023, QJRMS)

Conclusions:

- We look forward to AMF3!

- Yet, it would be great if opportunities were provided to enhance its capabilities through IOPs:

    - to capture the "**Ecosystem Scale Fluxes**"

    - understand the effect of canopy heterogeneity

    - further study turbulence anisotropy as a potential path to generalize MOST also over vegetated canopies.

Thanks