The study of atmospheric turbulent transport combining high-frequency measurements and numerical simulation

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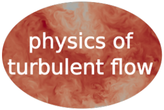
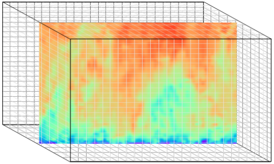
University of São Paulo, Brazil

November 5th, 2021

The atmospheric boundary layer

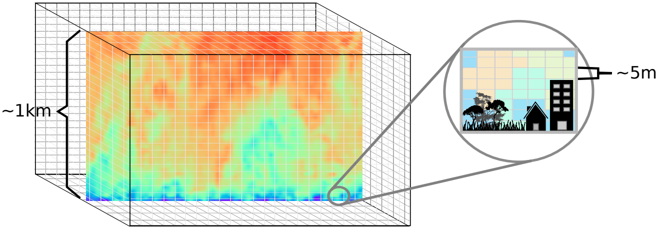


field and laboratory data



computational simulation

Computational Simulation



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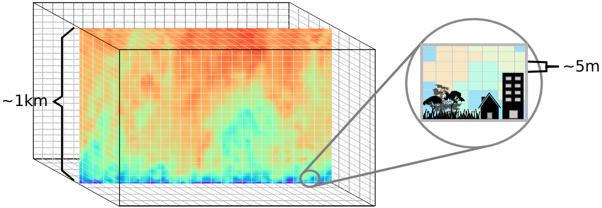

- written from governing equations: (approx.) “exact” solutions

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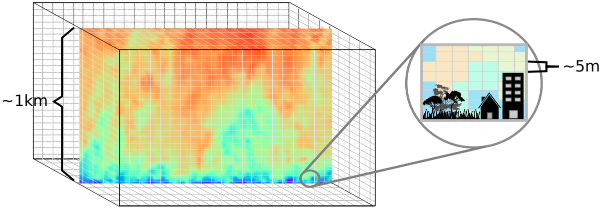

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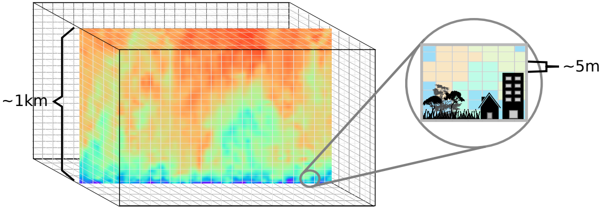
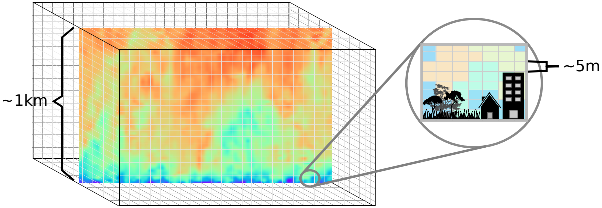
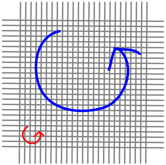


- written from governing equations: (approx.) “exact” solutions
- pros: controlled conditions, “isolation” of specific effects
- cons: simplified conditions (e.g. homogeneous, flat surfaces)

Direct Numerical Simulation (DNS): high computational cost



- solve Navier-Stokes + scalar transport equations
- domain: $\sim 1\,\mathrm{km}$
- grid size: $\sim 1\,\mathrm{mm}$



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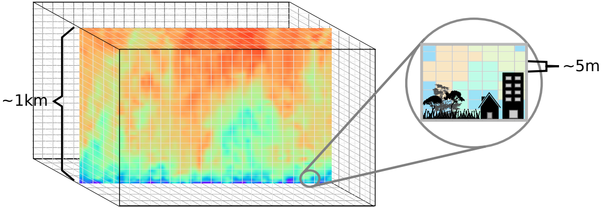
Large-Eddy Simulation (LES) of the ABL



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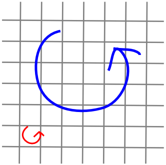
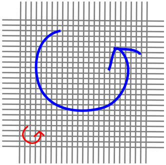
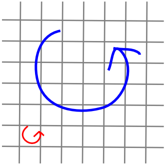
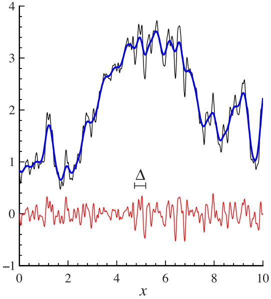


DNS versus LES





$$U = \widetilde{U} + u'$$



Adapted from Pope (2000)

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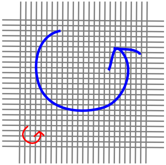
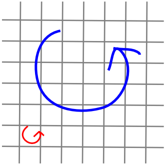
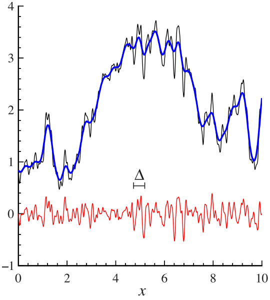




$$\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 U_i}{\partial x_j \partial x_j}$$



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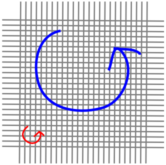
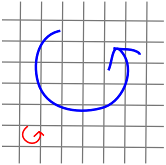
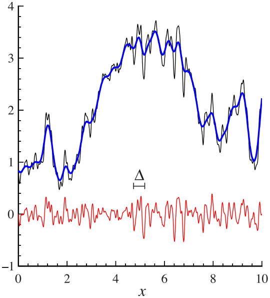




$$\frac{\partial \widetilde{U}_i}{\partial t} + \frac{\partial \widetilde{U}_i \widetilde{U}_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \widetilde{U}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}^R}{\partial x_j}$$



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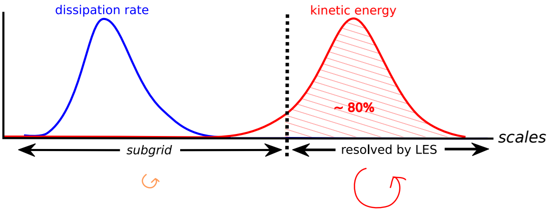
Large-Eddy Simulation (LES) of the ABL



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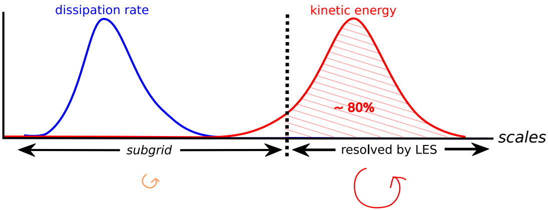

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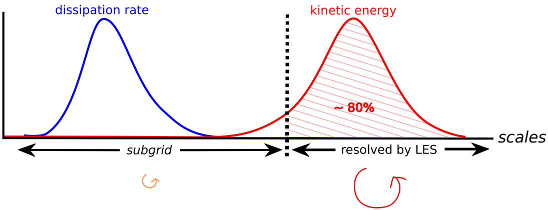

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- different τ_{ij}^{R} parameterizations: subgrid scale model

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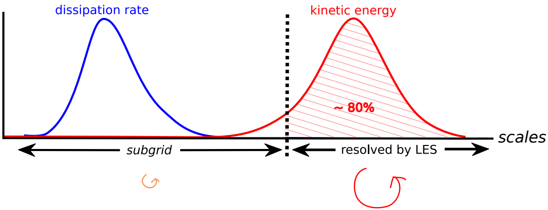

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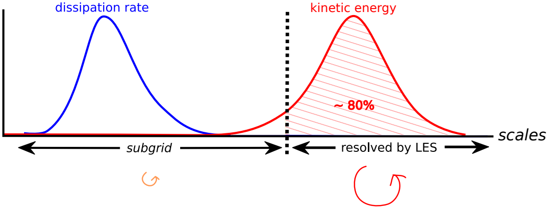

- solve filtered Navier-Stokes + scalar transport equations
- different τ_{ij}^{R} parameterizations: subgrid scale model
- different numerical method, mesh organization, boundary and initial conditions, etc
- research on development, testing and applications

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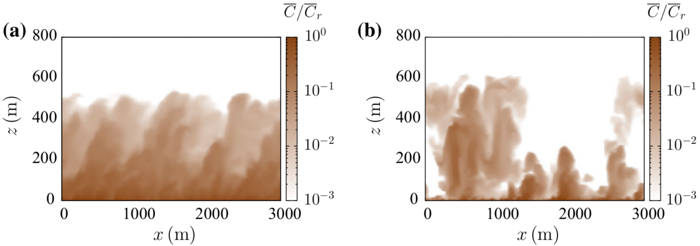
Example of ABL study using LES

mean concentration of small settling particles as a function of particle size and atmospheric stability:



$$\frac{\overline{u}}{u_*} = \frac{1}{\kappa}\left[\ln\left(\frac{z}{z_0}\right) + \psi(\zeta)\right]$$

$$\frac{\overline{C}}{C_r} = 1 - \frac{\Phi}{\kappa u_* C_r}\left[\ln\left(\frac{z}{z_r}\right) + \psi_c\left(\zeta, \frac{z_r}{L}\right)\right]$$

Freire et al. (2016) *Boundary-Layer Meteorol*

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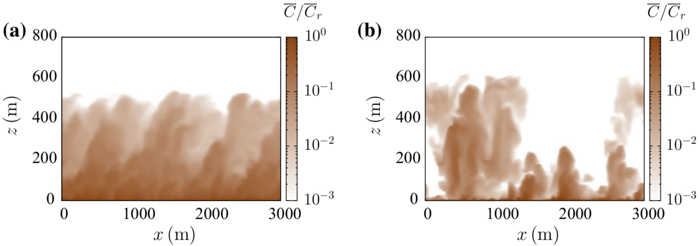

$$\frac{\partial \overline{C}}{\partial t} - w_s \frac{\partial \overline{C}}{\partial z} = D \frac{\partial^2 \overline{C}}{\partial z \partial z} - \frac{\partial \overline{wc}}{\partial z}, \qquad \overline{wc} = -\frac{\kappa z u_*}{\phi_c(\zeta)} \frac{\partial \overline{C}}{\partial z}$$

$$\frac{\overline{C}(z)}{\overline{C}_r} = \left(\frac{\Phi}{\overline{C}_r w_s} + 1 \right) \left(\frac{z}{z_r} \right)^{-\gamma} \exp(\gamma \psi_c(\zeta)) - \left(\frac{\Phi}{\overline{C}_r w_s} \right), \quad \gamma = \frac{w_s}{\kappa u_*}$$

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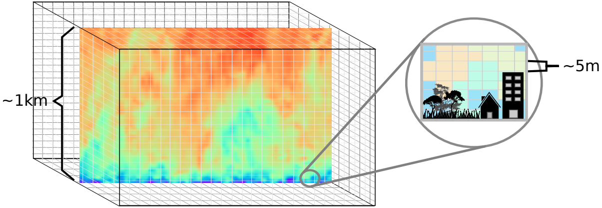
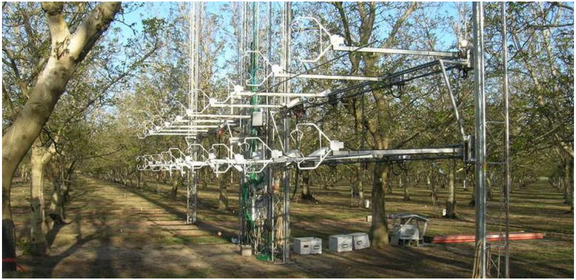
Computational Simulation



- approximate equations, simplified conditions
- validation with field measurements

Field measurements



(CHATS experiment `https://www.eol.ucar.edu/field_projects/chats`)

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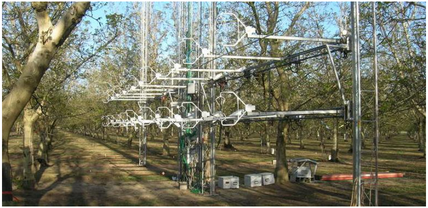

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- high-frequency time series (point measurements, arrays)

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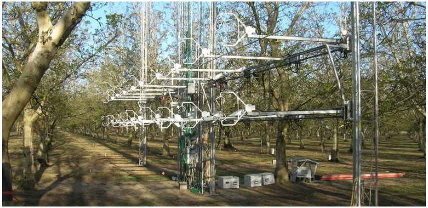
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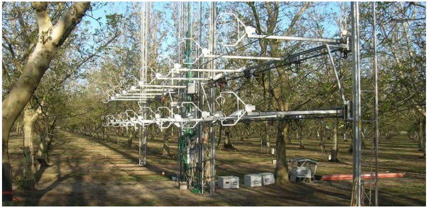

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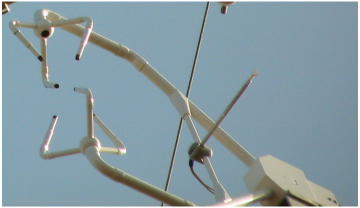
- high-frequency time series (point measurements, arrays)
- pros: measurement of “the reality”
- cons: uncontrolled, combination of many effects, sometimes difficult to interpret

Field measurements of velocity: hot-wire



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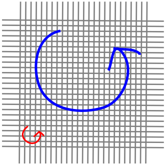
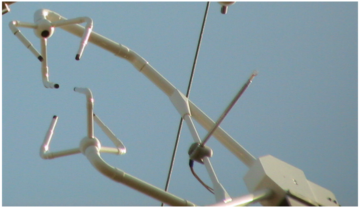
https://tsi.com/

- time series: many days
- measurement frequency: $\sim 2000\,\mathrm{Hz}$
- difficult, sensitive, frequent calibration



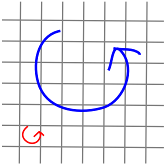
Field measurements of velocity: sonic anemometer



https://tsi.com/

(CHATS experiment https://www.eol.ucar.edu/field_projects/chats)

- time series: many days
- measurement frequency: $\sim 20\,\mathrm{Hz}$
- robust



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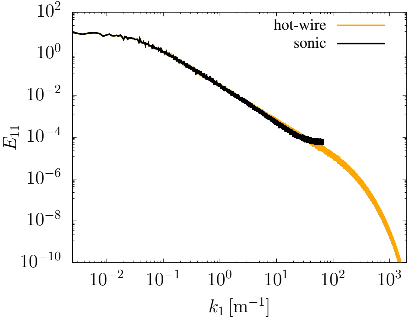

Freire et al. (2019) *Boundary-Layer Meteorol*
(ongoing research)

- data selection (stationarity, homogeneity, etc)
- statistical treatment
- errors of sensors
- research on sensor development, statistical analysis and applications

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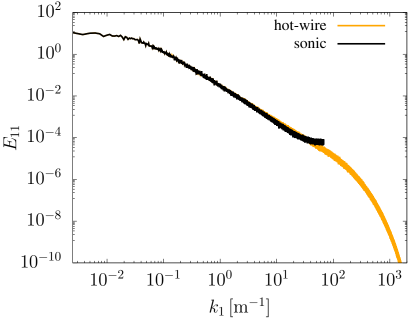

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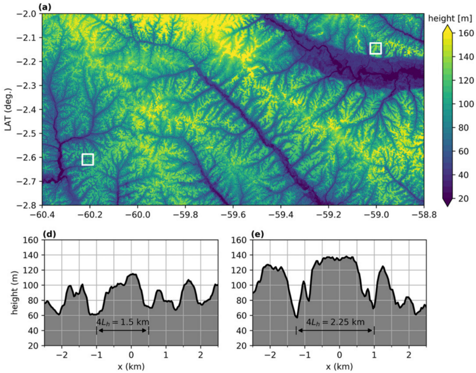
simulations can help on data interpretation

Example: effect of topography in the Amazon

Chamecki, Freire, Dias et al. (2020) *J Atmos Sci*



Reduced TKE budget:

$$P + B - \epsilon = R$$

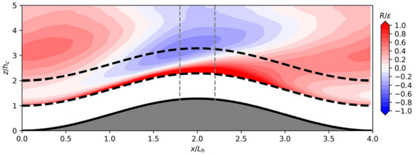


FIG. 9. Normalized local imbalance of TKE R/ε above the canopy from LES of the Amazon forest over idealized topography. The two thick black dashed lines indicate

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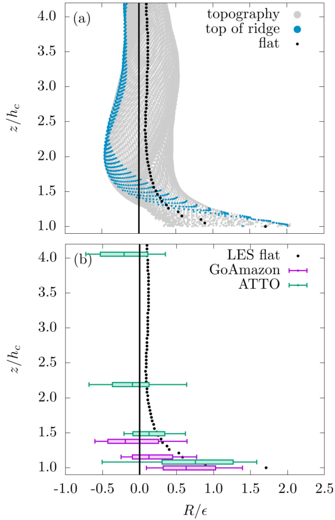

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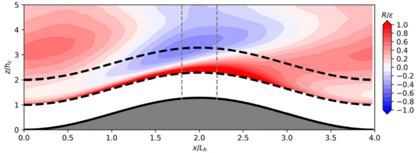

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Research opportunities:

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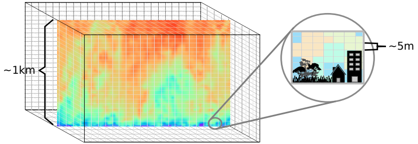
- testing
- applications



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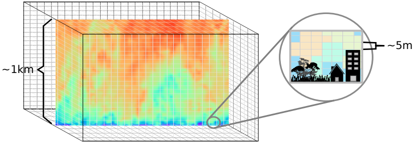

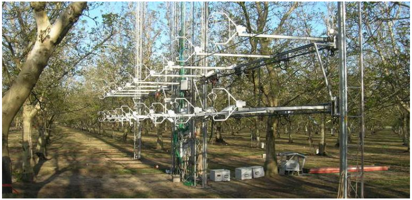

Research opportunities:

- sensor development
- error correction
- statistical approaches
- applications

- **Flux-Profile Relationship for Dust Concentration in the Stratified Atmospheric Surface Layer.** Freire, L.S., Chamecki, M., Gillies, J.A. (2016) *Boundary-Layer Meteorology*, 160(2), pp. 249-267
- **Effects of Path Averaging in a Sonic Anemometer on the Estimation of Turbulence-Kinetic-Energy Dissipation Rates.** Freire, L.S., Dias, N.L., Chamecki, M. (2019) *Boundary-Layer Meteorology*, 173(1), pp. 99-113
- **Effects of Vegetation and Topography on the Boundary Layer Structure above the Amazon Forest.** Chamecki, M., Freire, L.S., Dias, N.L., Chen, B., Dias-Junior, C.Q., Machado, L.A.T., Sörgel, M., Tsokankunku, A., de Araújo, A.C. (2020) *Journal of the Atmospheric Sciences*, 77(8), pp. 2941-2957

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