Physical modeling of atmospheric boundary layer flows

Part I: Overview of modeling concepts and techniques

Part II: Modeling neutrally stratified boundary layer flows

Evgeni Fedorovich
School of Meteorology, University of Oklahoma, Norman, USA

Outline

- **Place of physical modeling in the triad of approaches to study atmospheric boundary layer flows**
- **Concept of physical modeling: prototype versus model**
- **Commonly employed laboratory facilities and techniques**
- **Wind tunnel modeling of neutrally stratified boundary layers**
  - Methodology of generating neutral boundary layer flows in wind tunnels
  - Review of turbulent flow properties over rough and smooth surfaces
  - Similarity requirements; comparisons with atmospheric data
  - Tracer dispersion from a line source: numerical model evaluation
- **Summarizing remarks**

Triad of approaches in atmospheric boundary layer studies

I. Field observations/measurements

- *In situ*/contact measurements
- Remote sensing techniques

II. Physical/laboratory models

- Laboratory tank (thermal and saline) models
- Water channel/tunnel/flume models
- Wind tunnel (stratified and neutral) models

III. Theoretical/numerical techniques

- Theoretical/analytical models
- Numerical models/parameterizations
- Numerical simulations (direct and large-eddy)

I. Field observations/measurements

In situ/contact measurements and remote sensing techniques

Single global asset: it is real!

Hard or impossible to

- separate different contributing forcings/mechanisms
- match temporal/spatial requirements for retrieval of statistics
- control external forcings and boundary conditions
- obtain accurate and complete data at low cost

II. Physical/laboratory models

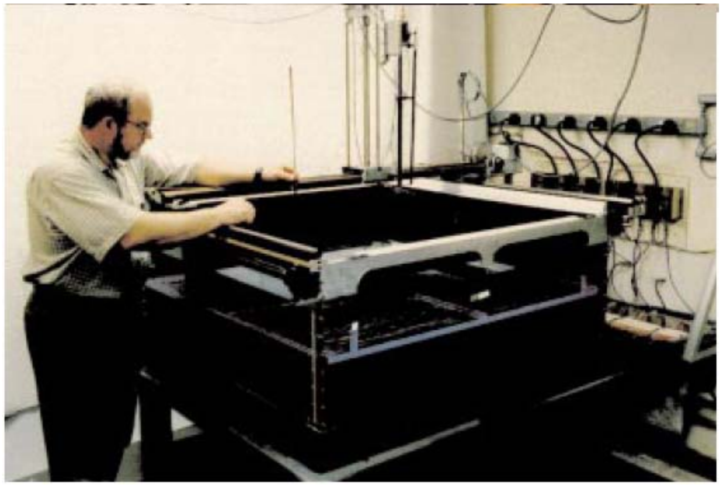
Laboratory tanks, water channels, wind tunnels

Pros:

- High level of complexity of modeled flows
- Controlled external/boundary parameters
- Repeatability of flow regimes
- Possibility to generate well-documented data sets for evaluation of numerical models/simulations

Hard or impossible to

- reproduce several contributing forcings in combination
- sufficiently match scaling/similarity requirements in order to relate the modeled flow to its atmospheric prototype
- find a reasonable balance between the value of results and cost of facility



III. Theoretical/numerical techniques

Analytical models, numerical models/parameterizations, numerical simulations

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p'}{\partial x_i} + b\delta_{i3} + \nu \frac{\partial^2 u_i}{\partial x_j \partial x_j}, \qquad \frac{\partial u_i}{\partial x_i} = 0$$

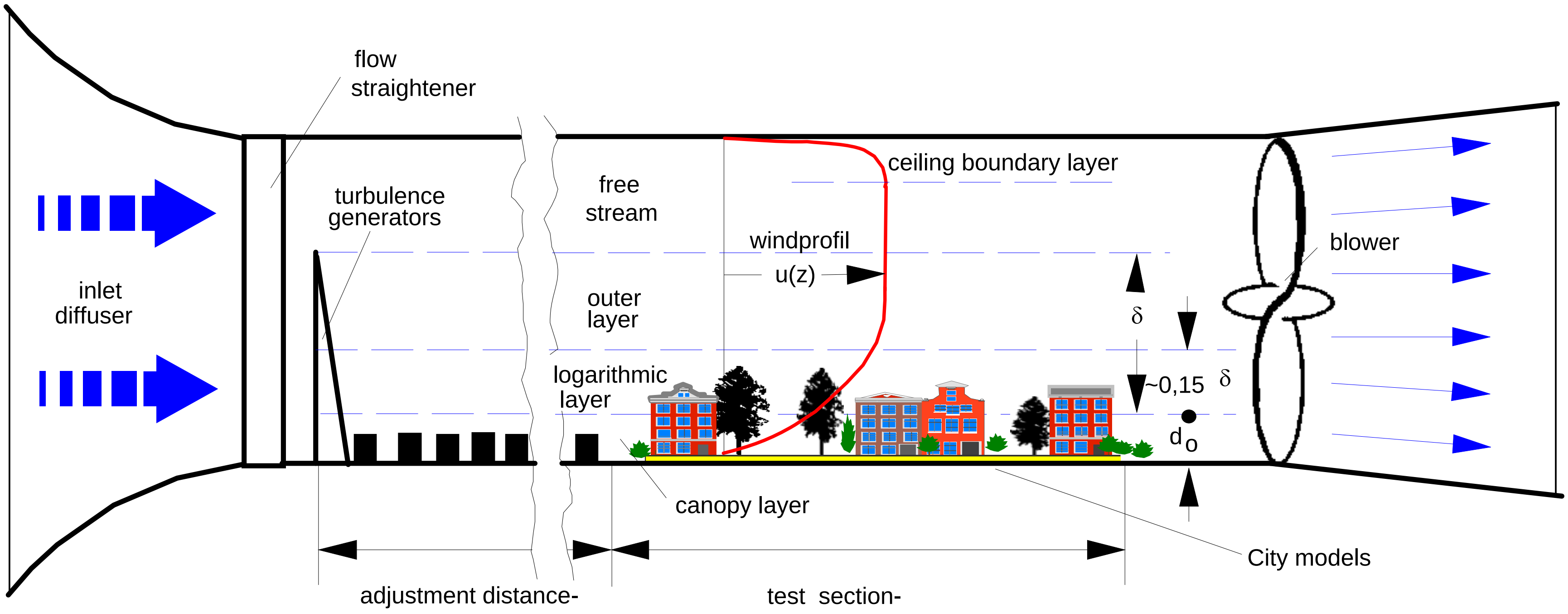
Pros:

- Availability at a relatively low cost
- Capability to generate instantaneous flow fields
- Accounting for processes within relatively broad ranges of temporal and spatial scales

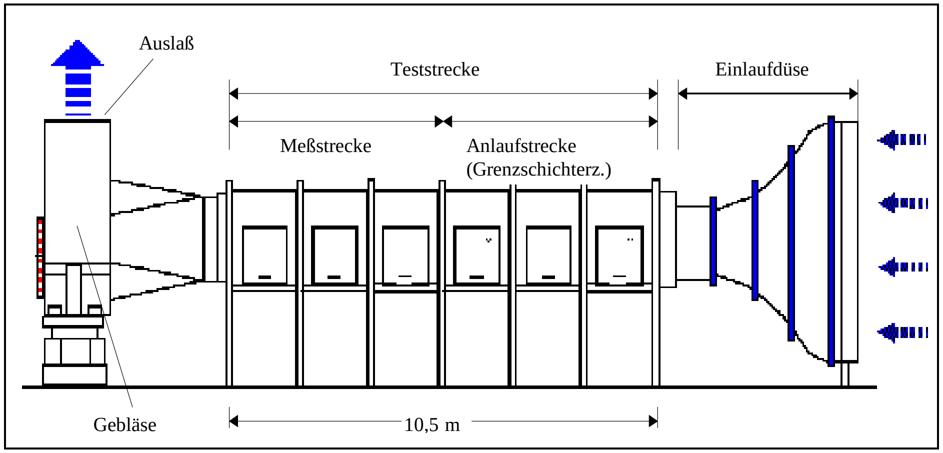
Hard or impossible to

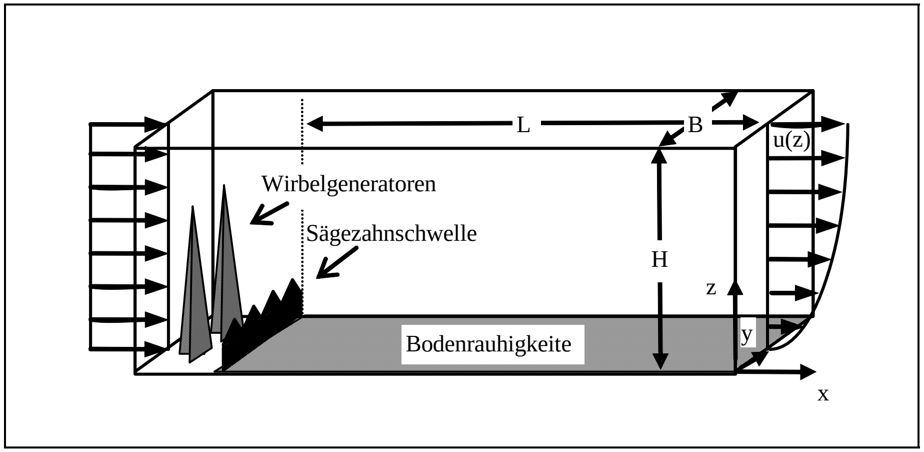
- reproduce flow regimes with realistic environmental settings
- evaluate precisely effects of subgrid/subfilter/ensemble turbulence closures
- separate numerical artifacts from actual physical features of the modeled/simulated flows

Wind tunnel modeling of neutral atmospheric BL flows



Design features of neutral boundary layer wind tunnels





Basic properties of a wall-bounded turbulent flow

Consider **turbulent flow** that is **parallel and horizontally homogeneous** in x direction (an idealization of a wind tunnel flow far away from the inlet) with mean (in Reynolds sense) velocity in this direction $u(z)$.

Prandtl concept of mixing distance/length l': particle that carries momentum between flow levels separated by distance l' instantly attributes momentum to surrounding air as it arrives to the destination level.

First-order approximation: $u(z+l') = u(z) + (\partial u/\partial z)l'$,

$u(z-l') = u(z) - (\partial u/\partial z)l'$, or,

in terms of velocity fluctuations, $u'(z+l') = u(z+l') - u(z) = l'(\partial u/\partial z)$,

$u'(z-l') = u(z-l') - u(z) = -l'(\partial u/\partial z)$.

Prandtl also supposed: $w' = -l'(\partial u/\partial z)\mathrm{sign}(u')$.

Multiplying w' with u' and averaging, we come to $\overline{u'w'} = -l^2(\partial u/\partial z)^2$,

where $l = \overline{l'^2}^{1/2}$ is the **mixing length** at level z, which may be interpreted as **characteristic integral turbulence length scale** for momentum exchange at level z.

Friction velocity and logarithmic wind profile

Another hypothesis/finding by Prandtl: $l \propto z$.

Vertical kinematic momentum flux is therefore: $\overline{u'w'} \propto -z^2 (\partial u / \partial z)^2$.

Von Kármán constant κ is a proportionality coefficient between l and z:

$$l = \kappa z,\ \overline{u'w'} = -\kappa^2 z^2 (\partial u / \partial z)^2.$$

From the flux-profile parameterization (**Boussinesq analogy**):

$$\overline{u'w'} = -k(\partial u / \partial z), \text{ where}$$

k is the **eddy viscosity** (turbulent exchange coefficient for momentum:

$$k = \kappa(-\overline{u'w'})^{1/2} z = \kappa^2 z^2 (\partial u / \partial z).$$

Near the wall $\overline{u'w'}$ is approximately height-constant and may be conveniently represented through the velocity scale $u_* = (-\overline{u'w'})^{1/2}$ called the **friction velocity**. Therefore, $k = \kappa u_* z$ or $k = u_* l$.

Also: $\partial u / \partial z = u_* / (\kappa z)$, which provides the **logarithmic velocity profile** in the near-wall region of the neutral boundary layer:

$$u = (u_* / \kappa) \ln z + C.$$

Aerodynamically smooth and rough surfaces

Based on **Reynolds-number criterion** Re=$u_*\delta_l / \nu \sim 1$ for laminarization of the flow close to the wall, one may expect that at distances from the wall of the order and less than $\delta_l \sim \nu / u_*$, the molecular shear stress ultimately dominates the turbulent stress: $-\overline{u'w'} \ll \nu(\partial u / \partial z)$.

Experimental data show: $\delta_l \approx 5\nu / u_*$. The layer defined in this manner is called the **viscous sublayer**.

Smooth surface: surface roughness elements of characteristic size h_r are deployed in the viscous sublayer: $h_r \ll \delta_l$.

Rough surface: $h_r \gg \delta_l$.

Laboratory experiments show that surface may be considered **aerodynamically smooth** for

$$h_r \leq 5\nu / u_*,$$

and **aerodynamically rough** when

$$h_r \geq 75\nu / u_*.$$

Wind profile over smooth and rough surfaces

Smooth-wall case: developed turbulent flow with $u = (u_* / \kappa) \ln z + C$ is realized at distances considerably larger than the length scale $\delta_l \sim \nu / u_*$.

Rough-wall case: flow is turbulent already in the immediate vicinity of surface roughness elements, with mean flow velocity vanishing (u=0) at some level close to h_r.

One may consider a reference level z_0 close to the surface, where u=0,

$$u = (u_* / \kappa) \ln(z / z_0).$$

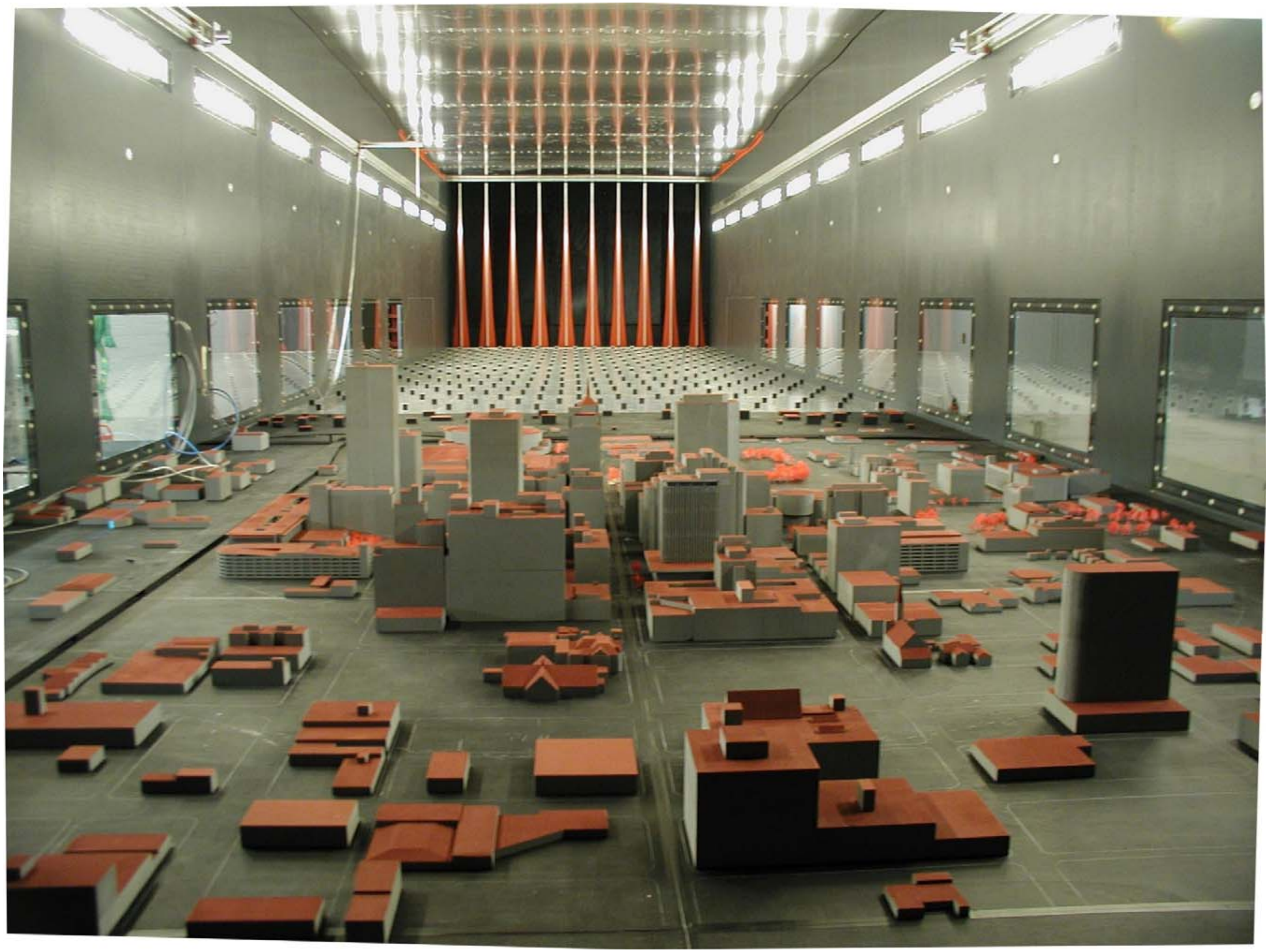
Quantity z_0 is called the **aerodynamic surface roughness length** or the **surface roughness length for momentum**.

Smooth-wall z_0 is retrieved from $u / u_* = (1/\kappa) \ln[z / (\nu / u_*)] + C_s$, where parameter $C_s = (1/\kappa) \ln[(\nu / u_*) / z_0]$ is about 5 (experiment):

$$z_0 = e^{-\kappa C_s} \nu / u_* \approx 0.1 \nu / u_*.$$

Rough-wall z_0 is a function of the surface geometry, involving h_r as one of parameters; generally speaking, z_0 is growing with h_r.

Interior of a modern neutral BL wind tunnel (WOTAN)



Wind profile approximations used in wind tunnel studies

Velocity profile above the rough surface starts to follow the logarithmic law only at some distance away from the surface, at $z >> z_0$. In this sense, the **surface roughness length is an asymptotic parameter** rather than a limiting point of the observed wind profile.

In order to make logarithmic wind profile applicable in a broader range of z close to the surface, it is often used with another parameter, the so-called **displacement height** d_0:

$$u = \frac{u_*}{\kappa} \ln \frac{z - d_0}{z_0}.$$

Along with log law, another analytical representation of wind profile is used (primarily, in wind engineering), the so-called **power law form:**

$$u(z) = u_{\text{ref}} \left(\frac{z - d_0}{z_{\text{ref}} - d_0} \right)^{\alpha},$$

where u_{ref} is u value at $z = z_{\text{ref}}$ and $\alpha < 1$ is an empirical exponent.

Similarity criteria for wind tunnel modeling of neutral BL flows

Length scales: $L_1 = z_0, \quad L_2 = d_0, \quad L_3 = \delta, \ldots$

Criteria: $(L_i / L_k)_{\text{model}} = (L_i / L_k)_{\text{nature}}$

Wind profile: $S_f = \dfrac{u(z)}{u_{\text{ref}}} = \left(\dfrac{z - d_0}{z_{\text{ref}} - d_0} \right)^{\alpha}, \ S_l = \dfrac{\kappa u(z)}{u_*} = \ln \dfrac{z - d_0}{z_0}.$

Criteria: $S_{f\,\text{model}} = S_{f\,\text{nature}}, \ S_{l\,\text{model}} = S_{l\,\text{nature}}$

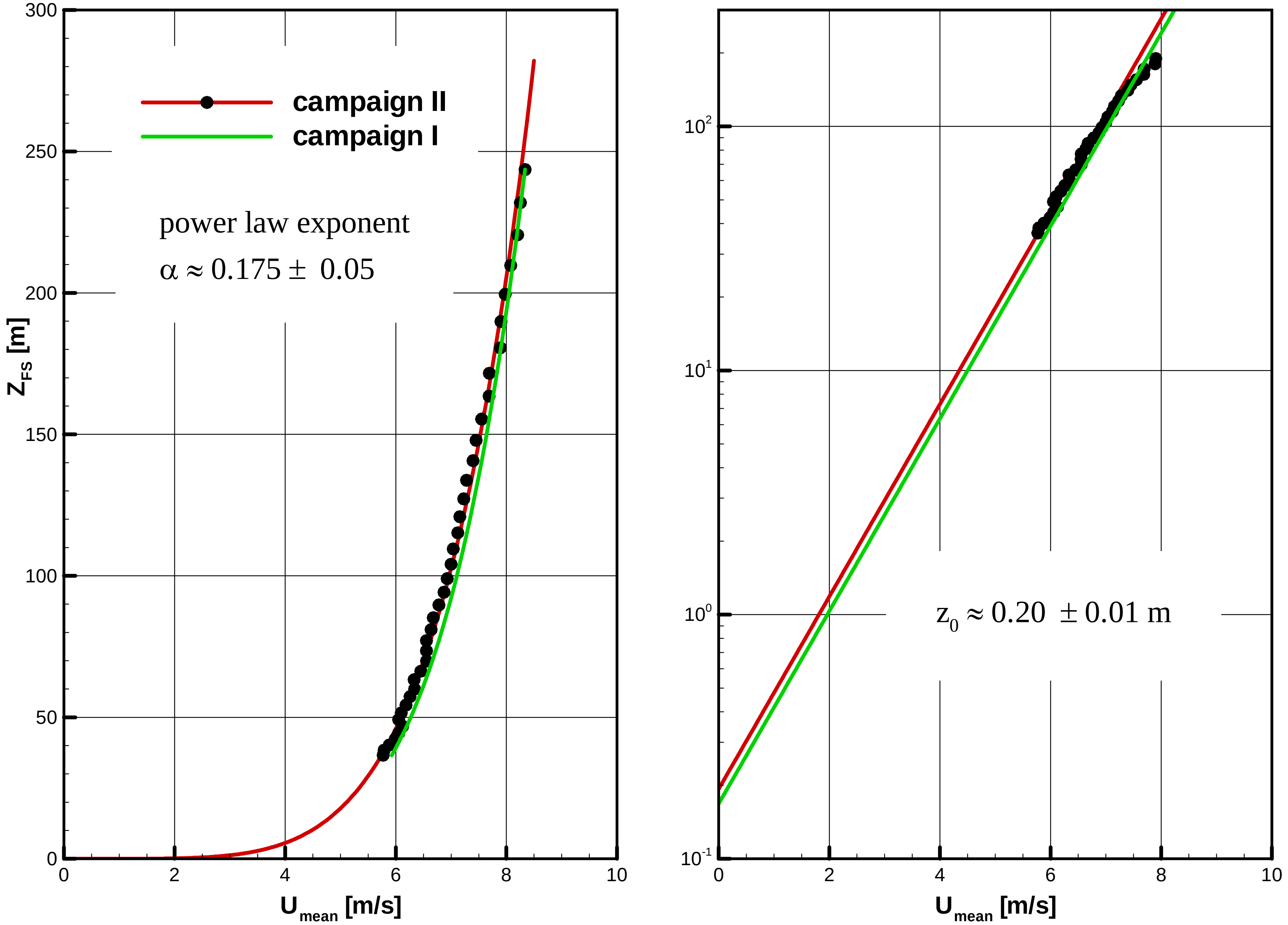
Turbulence intensity: $I_i = \sigma_i / u_i$, **and spectra:** $S_{ni} = k S_{ii}(k) / \sigma_i^2$.

Criteria: $I_{i\,\text{model}} = I_{i\,\text{nature}}, \ S_{ni\,\text{model}} = S_{ni\,\text{nature}}$

Surface roughness in the model: $\text{Re}_0 = \dfrac{u_* z_0}{\nu} >> 1,$

where $u_* = \left(-\overline{u'w'}\Big|_s \right)^{1/2}.$

Scaled mean wind profiles in WOTAN

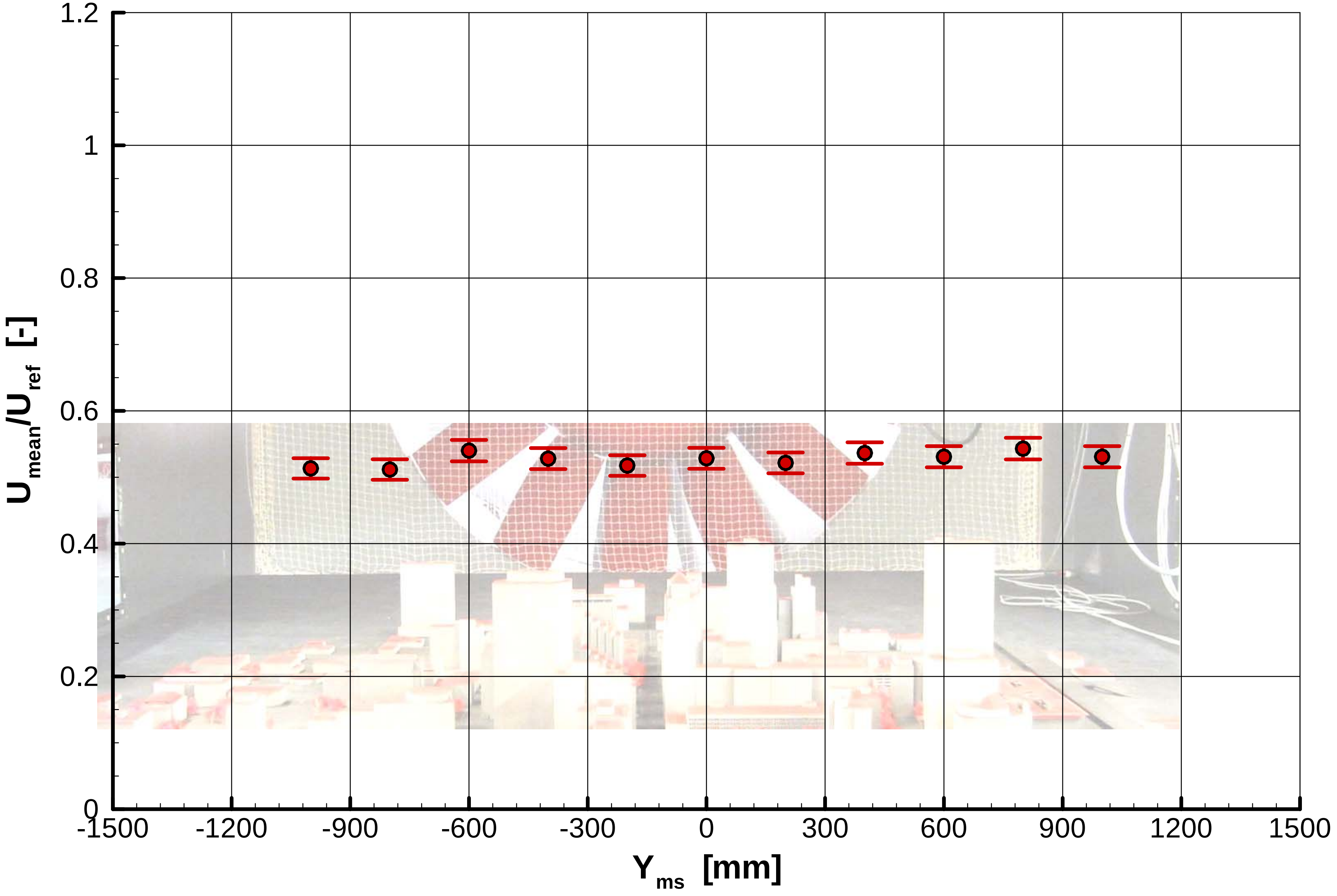


power law exponent

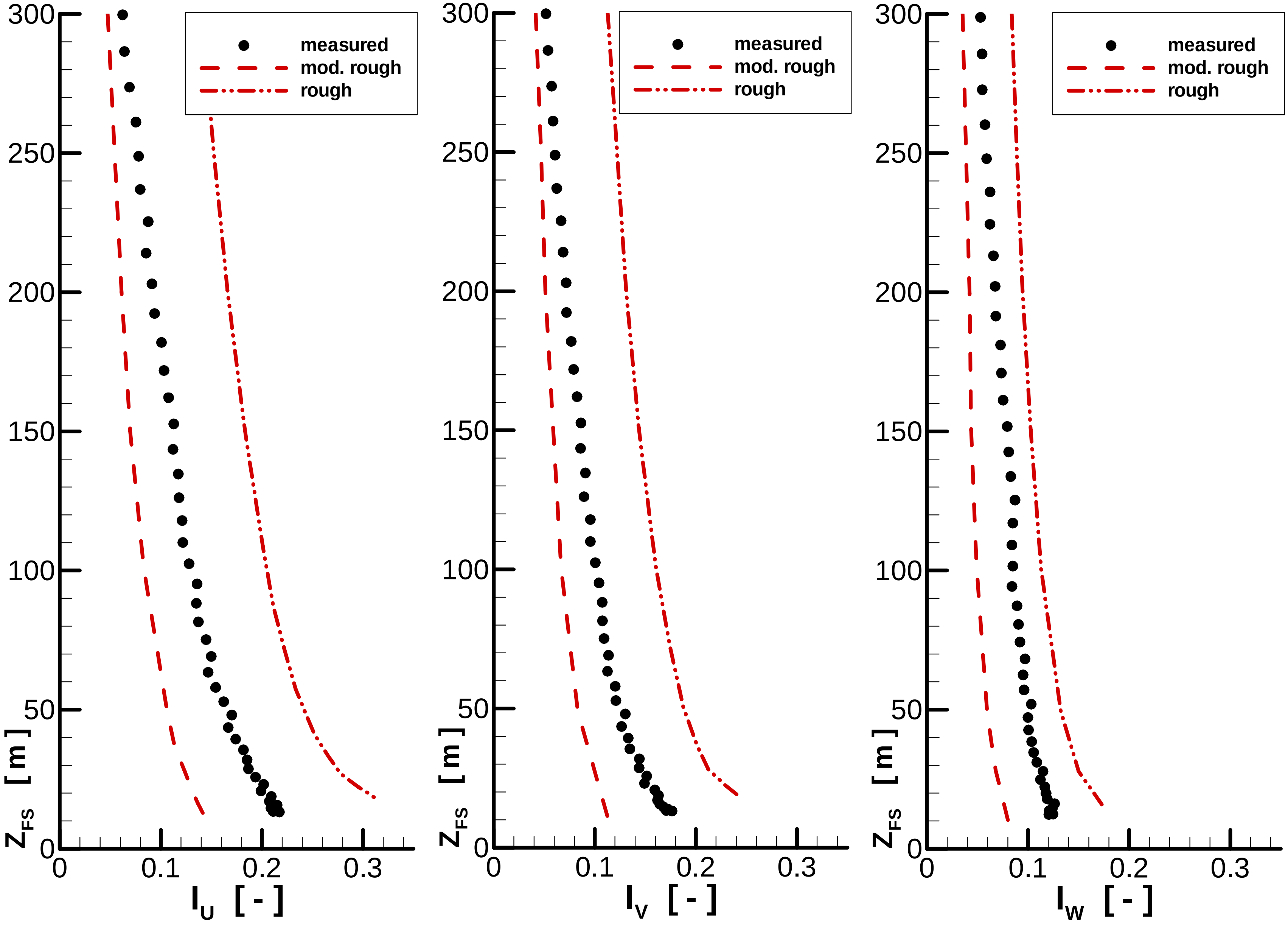
$\alpha \approx 0.175 \pm 0.05$

$z_0 \approx 0.20 \pm 0.01$ m

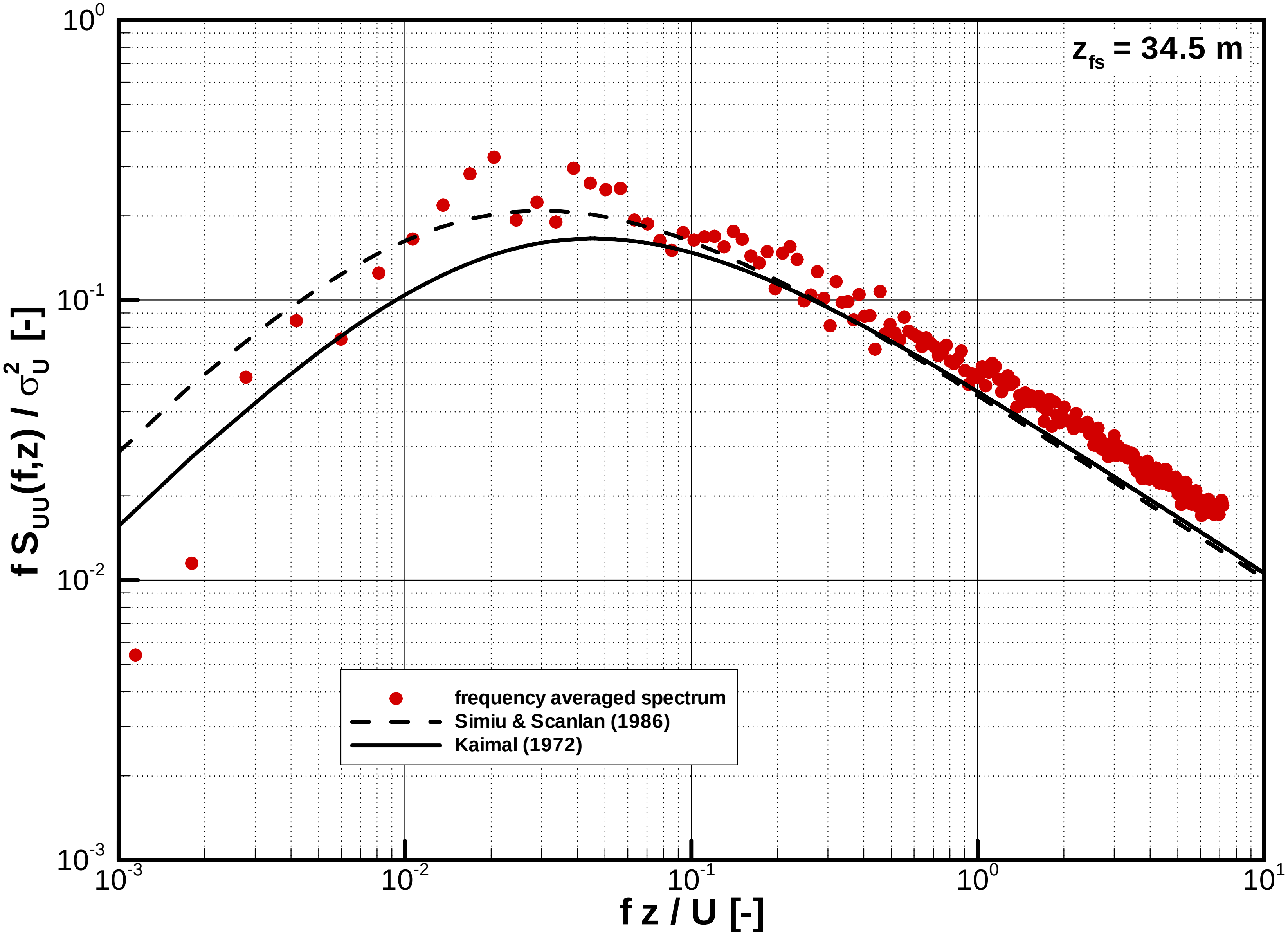
Lateral homogeneity of mean flow in WOTAN



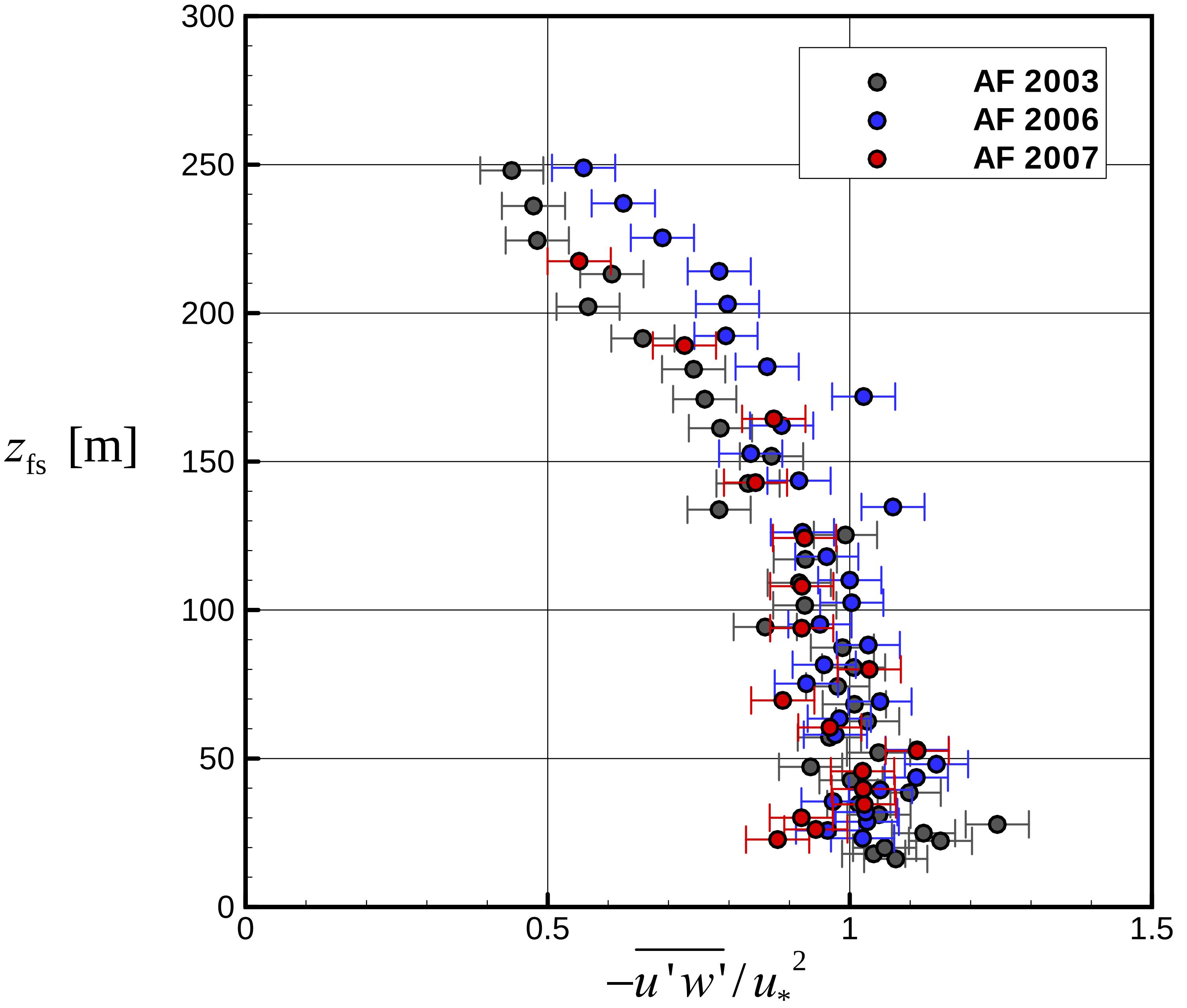
Intensities of turbulent velocity fluctuations in WOTAN



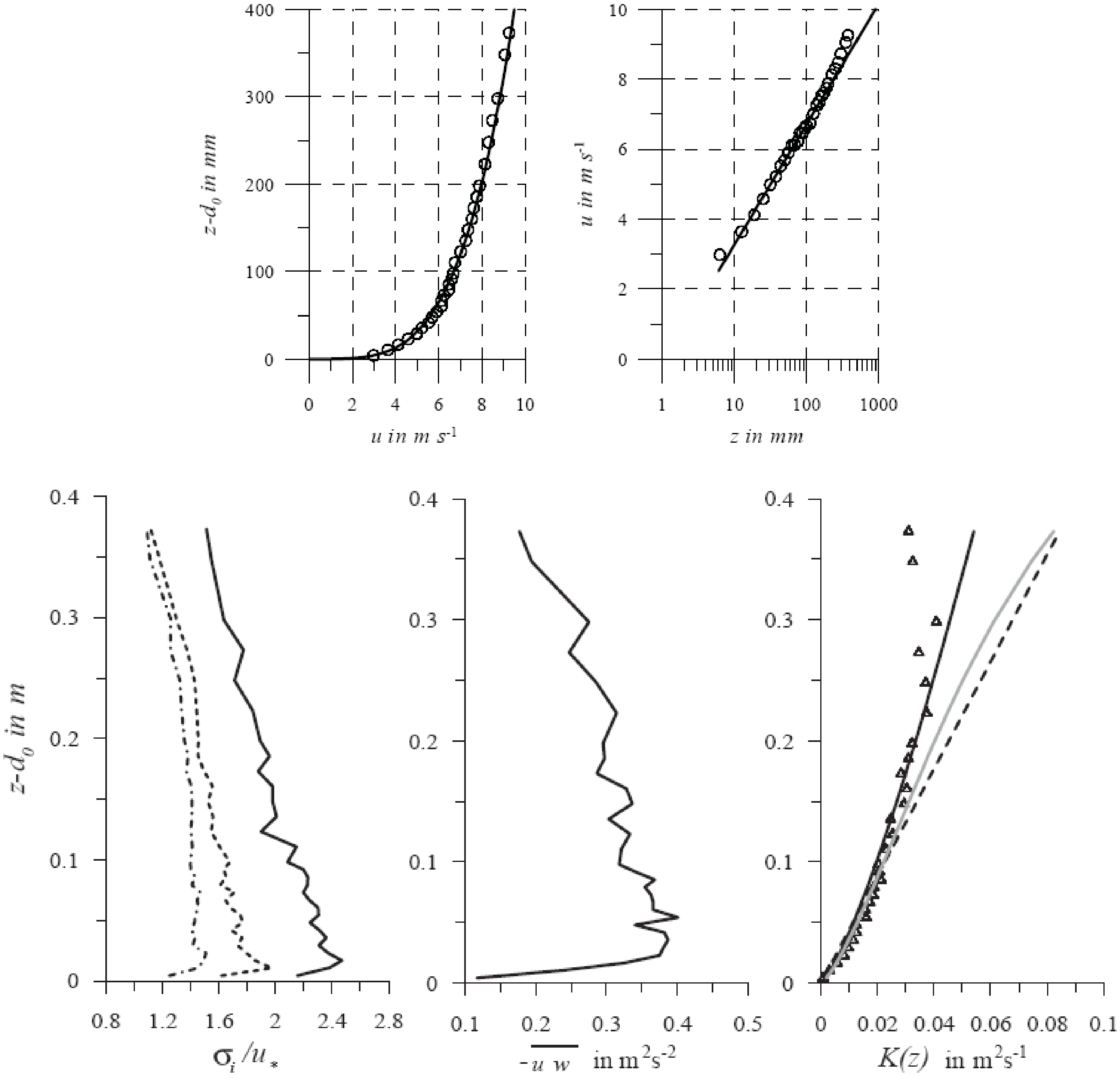
Longitudinal velocity component spectrum in WOTAN



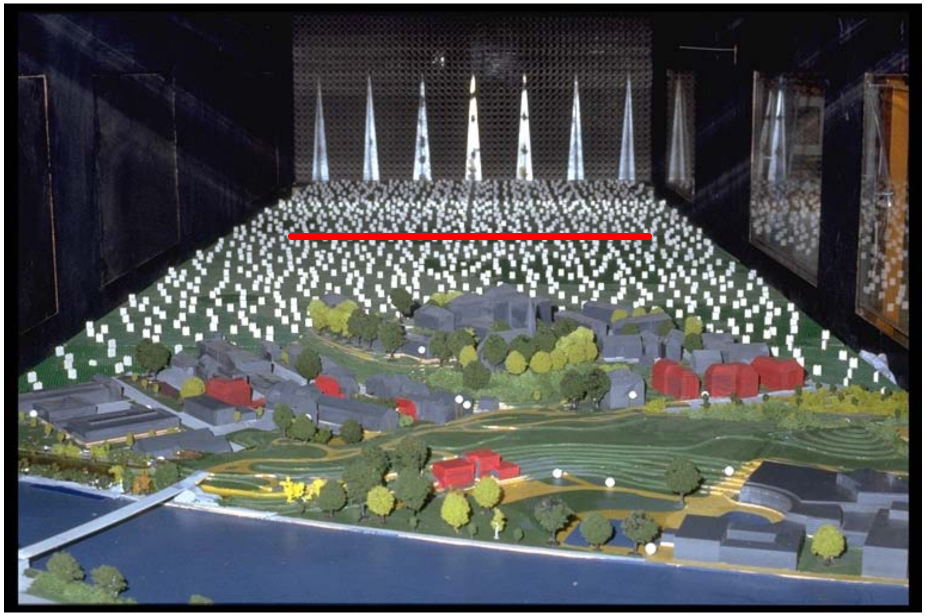
Vertical turbulent kinematic momentum flux in WOTAN



Flow parameters in the neutral boundary layer tunnel of UniKA



Dispersion of passive scalar from a ground line source



Schematic of the source (red line) deployed in the UniKA neutral WT

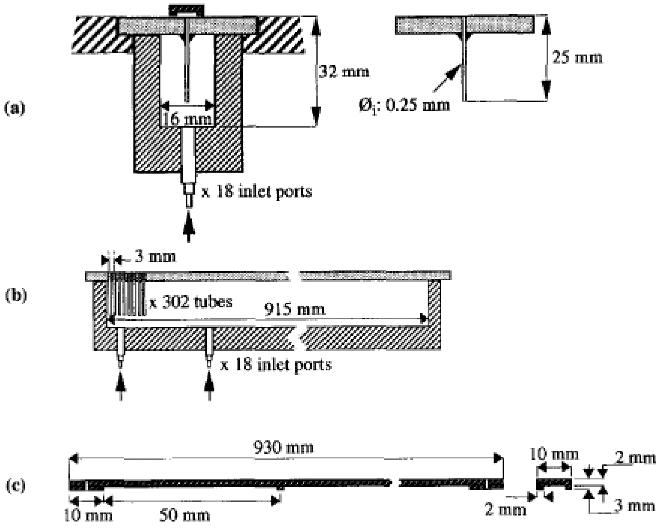
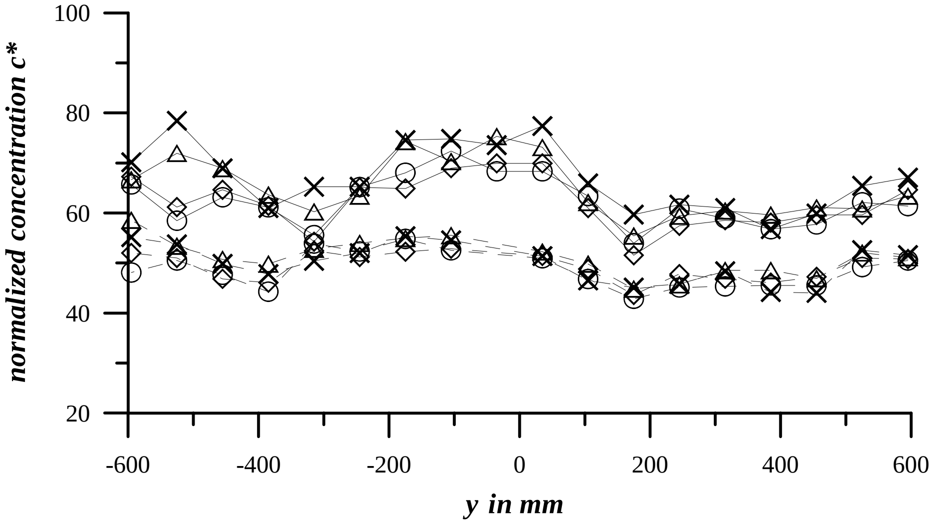


Fig. 6. Actual line source design. (a) Transverse cross section; (b) Longitudinal cross section; and (c) Capping brass bar.

Design of the line source after Meroney et al. (1996)

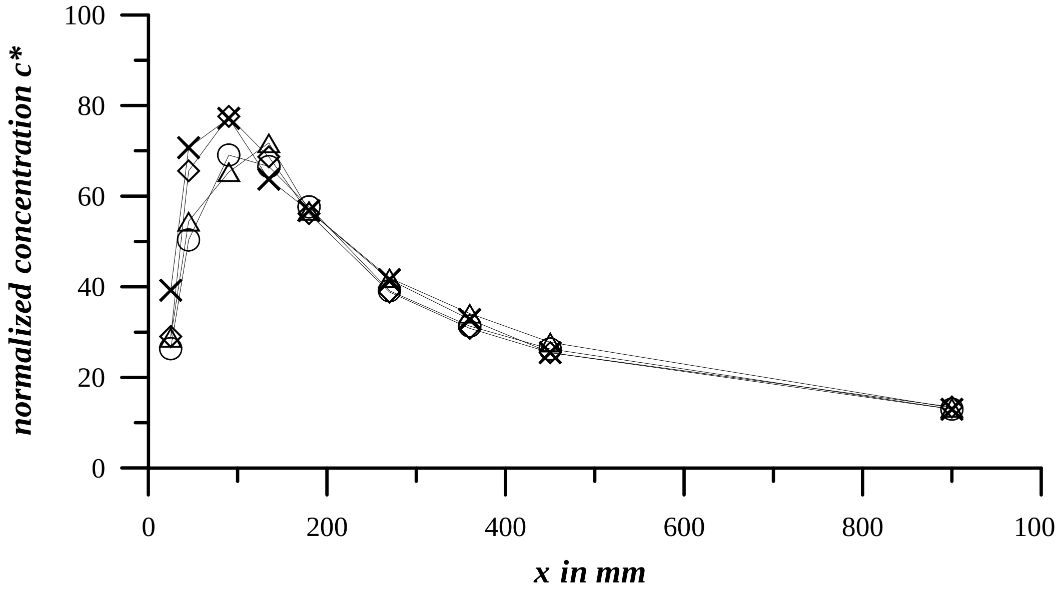


← **Normalized concentration**

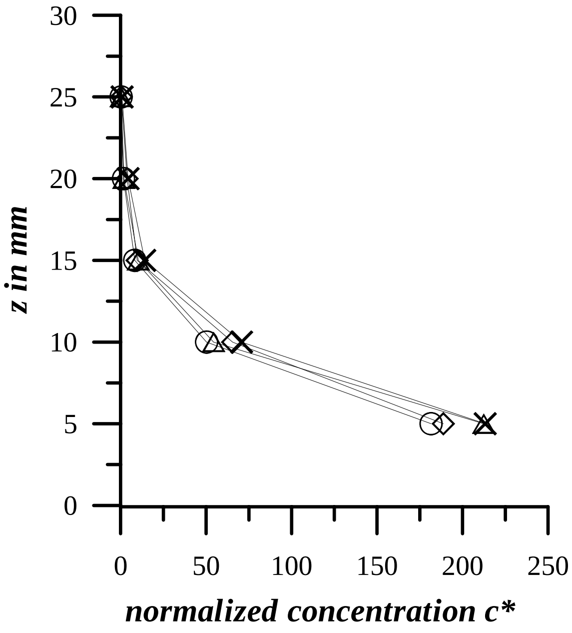
$$c^* = \frac{c u_{ref} z_{ref}}{Q_t}, \text{ where } Q_t \text{ is in } [\mathrm{L}^2\, \mathrm{T}^{-1}],$$

at z = 10 mm and x = 90 mm (solid lines) and x = 180 mm (dashed lines) for four test cases with different wind velocities and source flow rates.

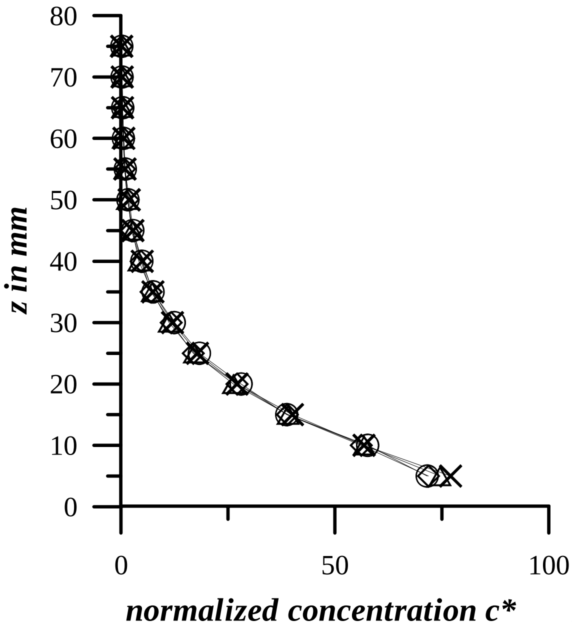
Longitudinal and vertical profiles of normalized concentration



at z=10 mm



at x=45 mm



at x=180 mm

Numerical model of dispersion from a ground line source

Balance equation for concentration *c* of a passive tracer is solved in a *x*-*z* plane perpendicular to the source located at x=0, z=0:

$$u(z)\frac{\partial c}{\partial x} = \frac{\partial}{\partial z} K_c(z)\frac{\partial c}{\partial z} + I_s .$$

Mean velocity profile is assumed to be logarithmic: $u(z) = \frac{u_*}{\kappa}\ln\frac{z}{z_0}$.

Eddy diffusivity linearly depends on height as $K_c(z) = \kappa u_* z / \mathrm{Sc}_t$, where Sc_t is the **turbulent Schmidt number**.

Boundary conditions: $\partial c / \partial z = 0$ at $z = z_0$ and c=0 at $z = \delta_l$.

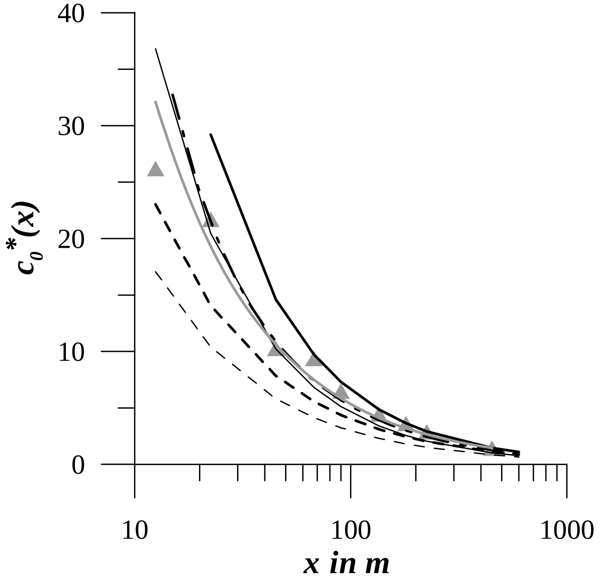
Friction velocity is determined from $u_* = \kappa u_l / (\ln \delta_l / z_0)$.

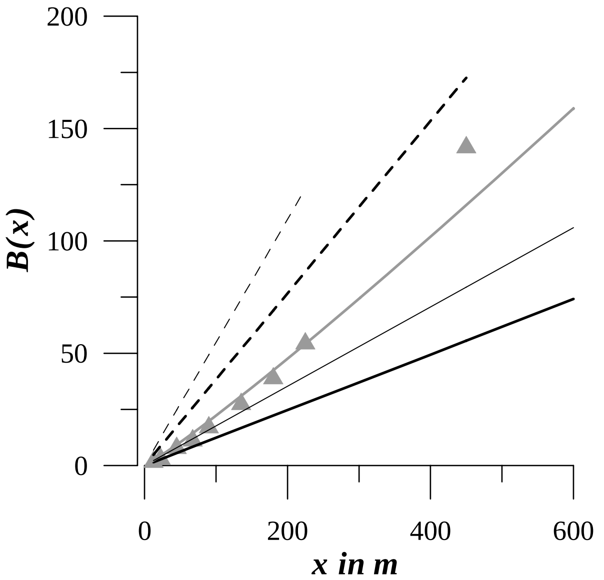
$I_s = Q_s / (\Delta x_1 \Delta z_1)$ is the **source function**, where $\Delta x_1 \Delta z_1$ is the cross-section area of the numerical grid cell surrounding the source. Elsewhere in the model domain outside this cell: $I_s = 0$.

Numerical solution: implicit integration over x and factorization over z.

Model verification against the wind tunnel data

Ground-level concentration (left plot)



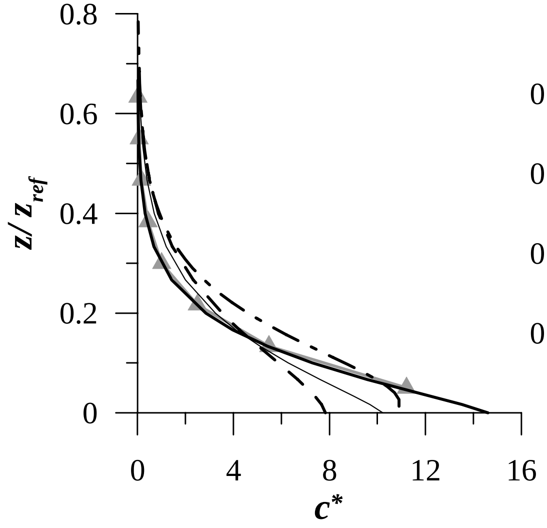


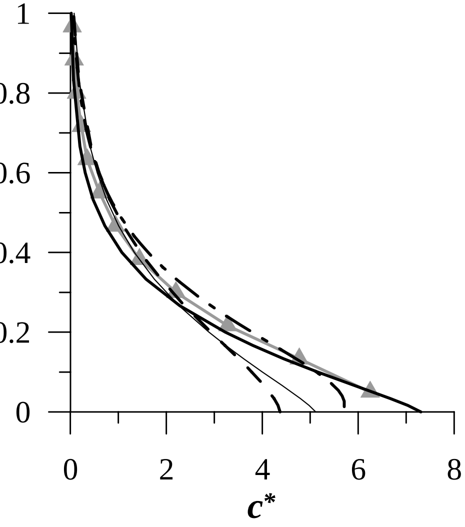
Wind tunnel data are gray symbols and lines.

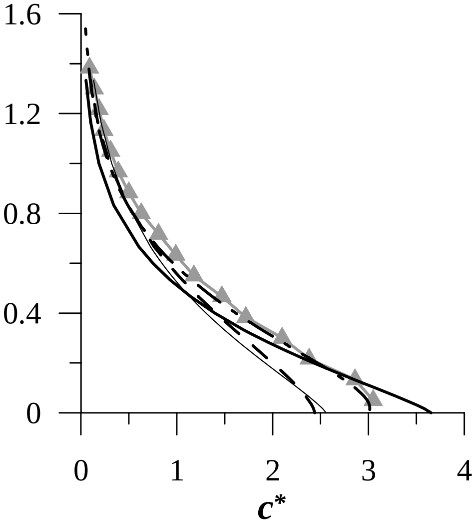
Dashed-dotted line shows numerical data for $\mathrm{Sc}_t = 1$.

Other lines represent different analytical solutions considered in Kastner-Klein and Fedorovich (2002).

Concentration profiles at *x* = 45 m (left), *x* = 90 m (center), and *x* = 180 m (right)







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