Aerodynamic resistance parametrization for heterogeneous surfaces using a covariance function approach

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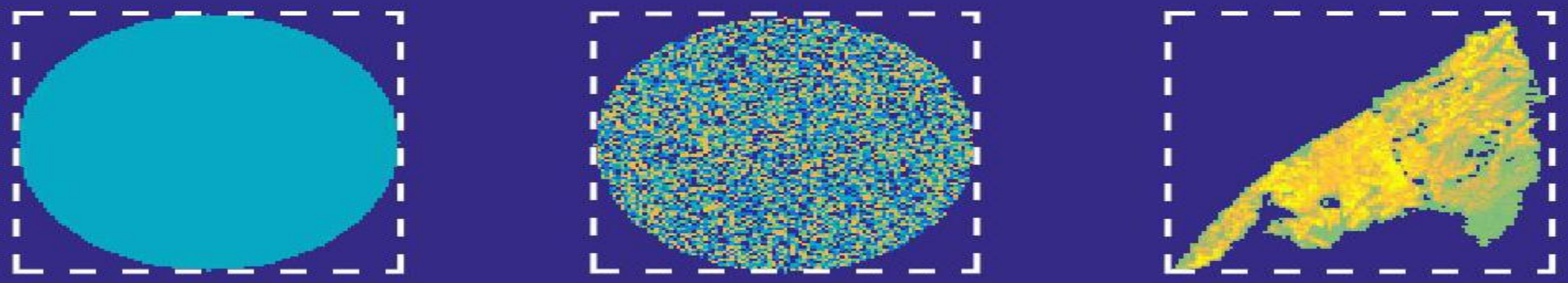


Motivation

- Meso-scale models have a typical resolution of order $1\ \mathrm{km} - 100\ \mathrm{km}$

→ Many important scales of surface heterogeneity not resolved

→ Large inaccuracies for distinct surface heterogeneities (mountainous areas, semi-arid forests, …)

Motivation

Garmisch-Partenkirchen, Germany

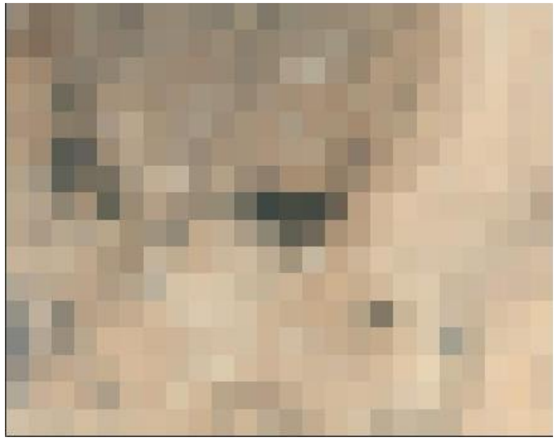
$\Delta x = 0.5\ \mathrm{km}$

$\Delta x = 2\ \mathrm{km}$

Yatir forest, Israel

$\Delta x = 0.5\ \mathrm{km}$

$\Delta x = 2\ \mathrm{km}$



→ Subgrid scale parametrizations needed

Introduction: Monin-Obukhov similarity (MOST)

MOST used for most subgrid scale parametrizations

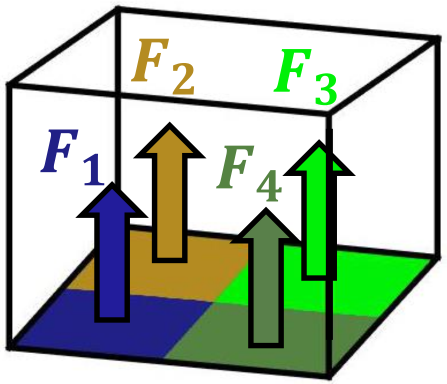
surface properties (z_0, u_*, $\overline{w'\theta'}_0$, …) → MOST → flow quantities at z ($\overline{u}_i(z)$, $\overline{\theta}(z)$, $\overline{q}(z)$)

⚠ MOST developed for homogeneous surfaces

→ Direct application of MOST to heterogeneous surfaces (bulk similarity) only for weakly heterogeneous scenarios

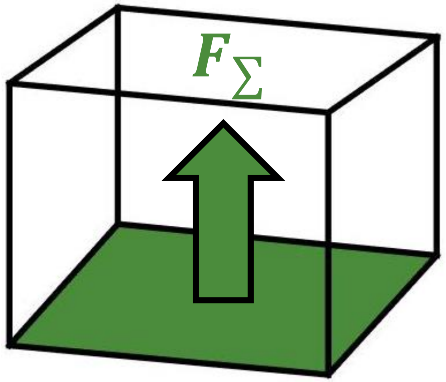
→ Other methods of applying MOST to heterogeneous surfaces → “Discrete” approaches

Introduction: Discrete approaches / tile method

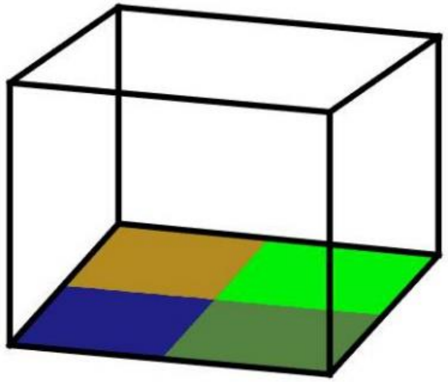


$$F_{\Sigma} = \sum_i \nu_i F_i$$

weighting factors



- Fragmentation of grid cell into land surface types
- Application of MOST to every surface type individually
- Aggregation of patches to determine effect of grid cell → flux aggregation
- Tile approach: Weighting factors from percentage of coverage



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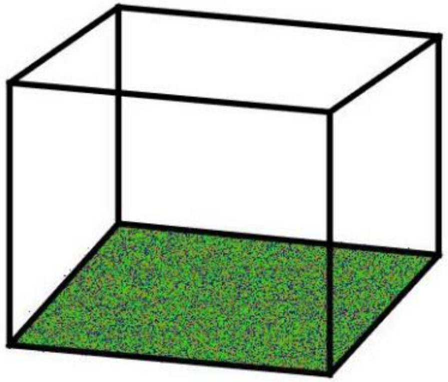


No spatial organization of tiles

Introduction: Bulk/tile aerodynamic resistance

Aerodynamic resistance for heat transfer: $r = \frac{\overline{T}_0 - \overline{T}(z)}{\overline{w'T'}_0}$

- Bulk approach: Direct application of MOST:

$$r_{\text{bulk}} = \frac{1}{\kappa^2 U} \int_{z_{0m}}^{z} d\tilde{z}\, \frac{\phi_m(\tilde{z}/L)}{\tilde{z}} \int_{z_{0h}}^{z} d\tilde{z}\, \frac{\phi_h(\tilde{z}/L)}{\tilde{z}}$$

Obukhov length (atmospheric stability)

von Karman constant (≈ 0.41)

Wind speed

Roughness lengths

Stability correction functions

- Tile approach: Using r_{bulk} for every surface patch to calculate $\overline{w'T'}_i$

$$\overline{w'T'}_\Sigma = \sum_i \nu_i \overline{w'T'}_i$$

$$\left(\langle\overline{T}\rangle_0 - \langle\overline{T}\rangle(z)\right)/r_{\text{tile}} = \sum_i \nu_i \left(\langle\overline{T}\rangle_{i,0} - \langle\overline{T}\rangle(z)\right)/r_{\text{bulk},i}$$

Average over MSM grid cell

Average for tile i

Theory: Covariance function approach

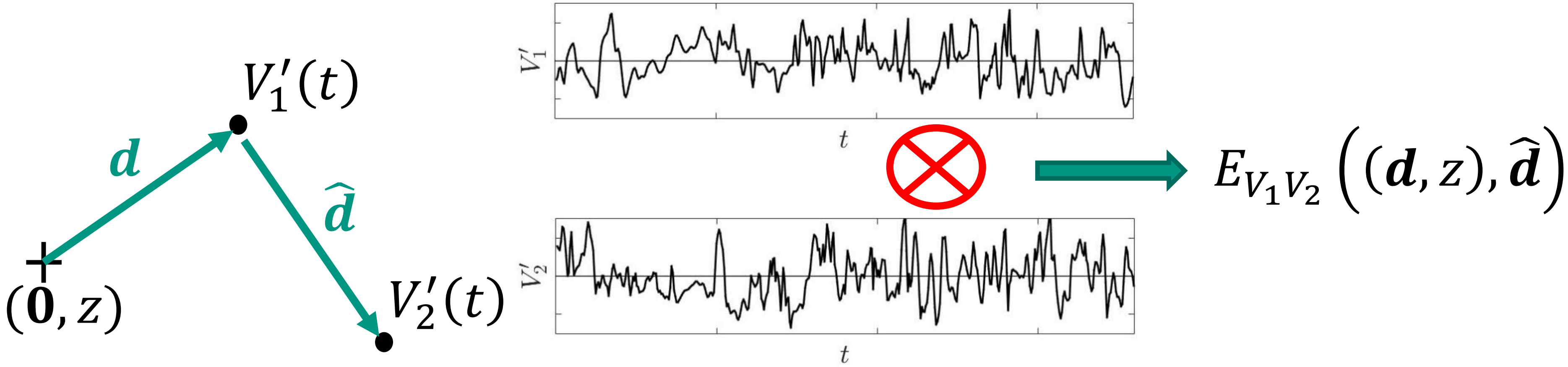
Bulk & tile approaches do <u>not</u> respect all scales of heterogeneity

→ Derivation of a novel parametrization from covariance functions

→ Better representation of turbulence characteristics (Kolmogorov, Townsend)

<u>Def</u>: Covariance function for two flow variables V_1 and V_2

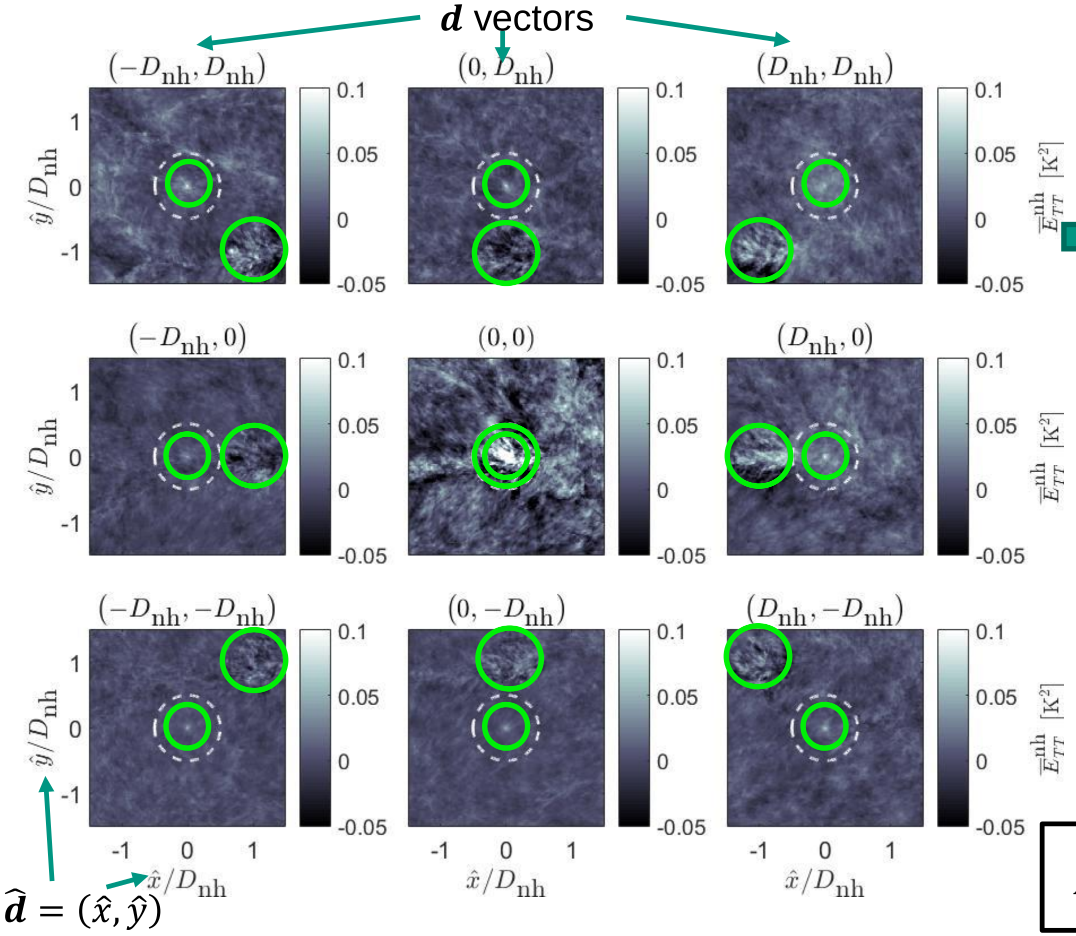
$$E_{V_1 V_2}\left((\boldsymbol{d}, z), \hat{\boldsymbol{d}}\right) = \overline{V_1'(\boldsymbol{d}, z)\, V_2'(\boldsymbol{d} + \hat{\boldsymbol{d}}, z)}$$

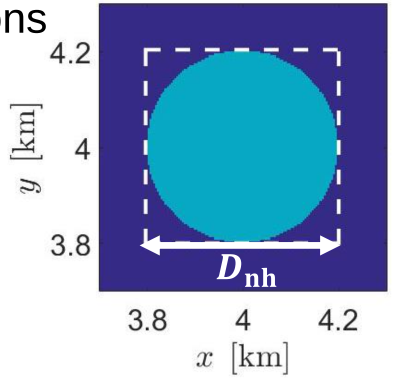


Theory: homogeneous → heterogeneous

Correlate homogenous ($E^{\mathrm{h}}_{V_1V_2}$) and heterogeneous ($E^{\mathrm{nh}}_{V_1V_2}$) covariance functions

→ Plot E^{nh}_{TT} from large-eddy simulation (LES) of circular heterogeneity:
($\Delta x = \Delta y = \Delta z = 4$ m, $N_x \times N_y \times N_z = 2000 \times 2000 \times 400$, $U_{bg} = 1\ \mathrm{m\,s^{-1}}$)





→ E^{nh}_{TT} consists of two functions

- Maximum at $\hat{\boldsymbol{d}} = \boldsymbol{0}$
  → E^{h}_{TT}
- Surface heterogeneity, shifted by $-\boldsymbol{d}$
  → Heterogeneity map χ

$$E^{\mathrm{nh}}_{TT}\left((\boldsymbol{d}, z), \hat{\boldsymbol{d}}\right) = \chi(\boldsymbol{d} + \hat{\boldsymbol{d}})\, E^{\mathrm{h}}_{TT}(\hat{\boldsymbol{d}}, z)$$

Theory: r_{cf} derivation from covariance functions

$$E_{TT}^{\mathrm{nh}}\left((\boldsymbol{d}, z), \widehat{\boldsymbol{d}}\right) = \chi\left(\boldsymbol{d} + \widehat{\boldsymbol{d}}\right) E_{TT}^{\mathrm{h}}\left(\widehat{\boldsymbol{d}}, z\right)$$

Kolomogorov spectra

Eddy anisotropy for non-neutral stratification (Katul et al, 2011)

Covariance function approach to calculate r_{cf}

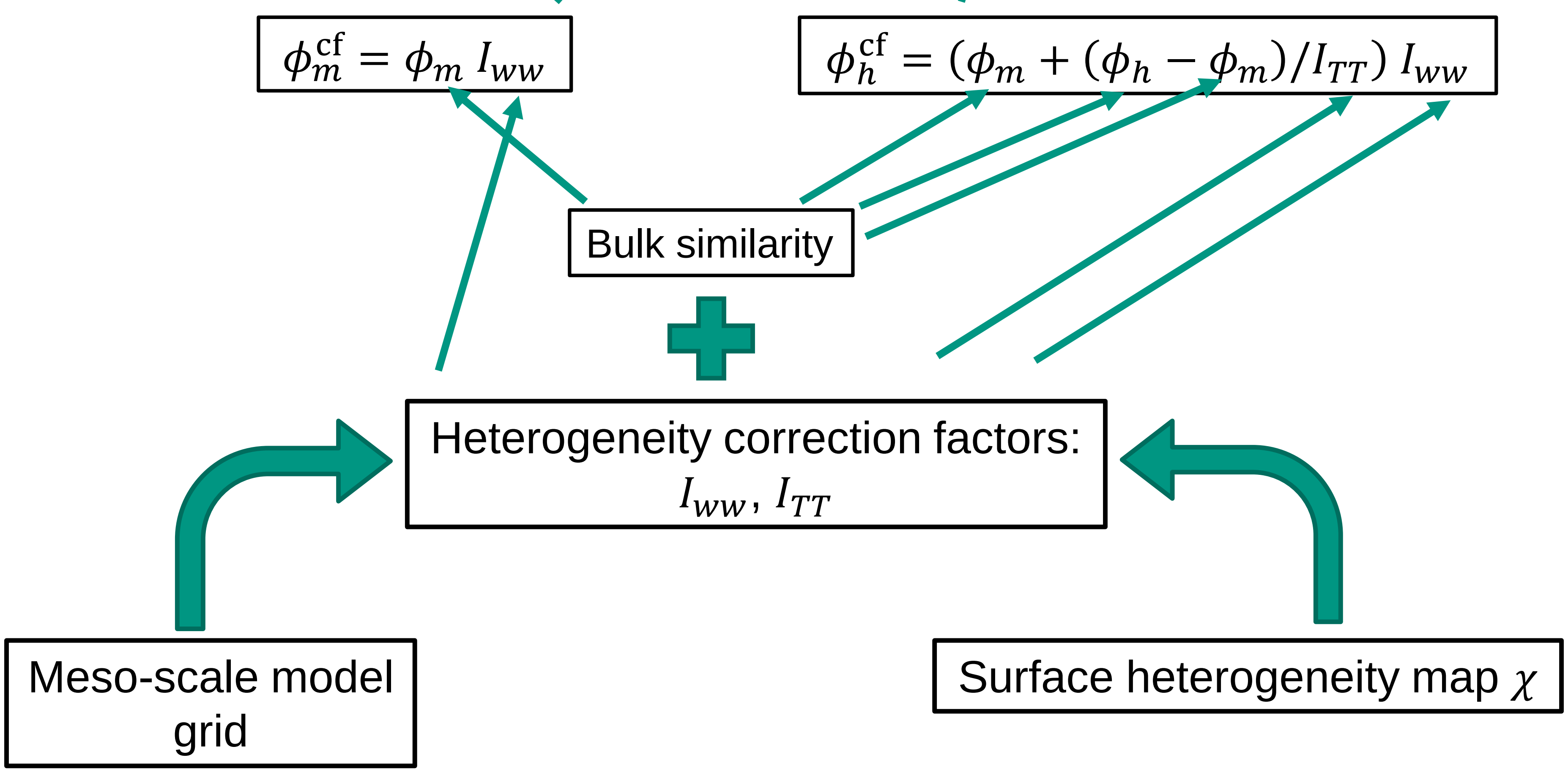
Analytical derivation, neglecting dispersive fluxes and advection

Heterogeneity corrections for r_{bulk}

$$r_{\mathrm{cf}} = \frac{1}{\kappa^2 U} \int_{z_{0m}}^{z} d\tilde{z}\, \frac{\phi_m^{\mathrm{cf}}(\tilde{z}/L)}{\tilde{z}} \int_{z_{0h}}^{z} d\tilde{z}\, \frac{\phi_h^{\mathrm{cf}}(\tilde{z}/L)}{\tilde{z}}$$

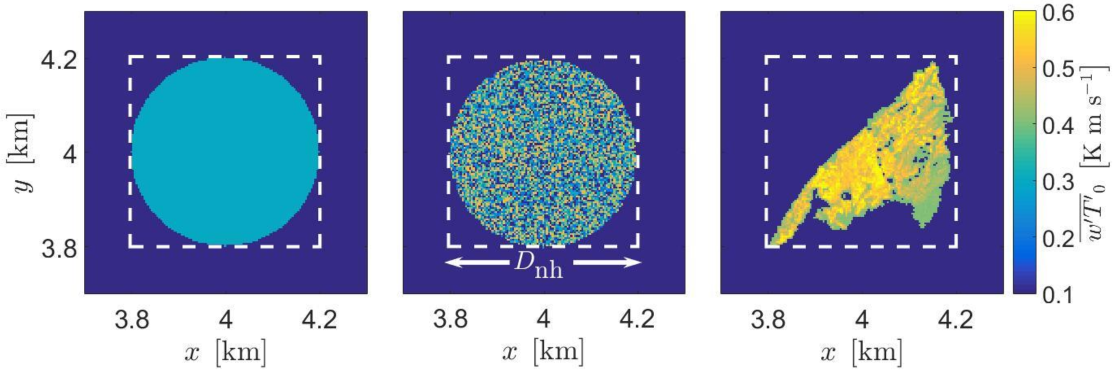
Theory: Heterogeneity corrections

$$r_{\mathrm{sf}} = \frac{1}{\kappa^2 U} \int_{z_{0m}}^{z} d\tilde{z} \, \frac{\phi_m^{\mathrm{cf}}(\tilde{z}/L)}{\tilde{z}} \int_{z_{0h}}^{z} d\tilde{z} \, \frac{\phi_h^{\mathrm{cf}}(\tilde{z}/L)}{\tilde{z}}$$



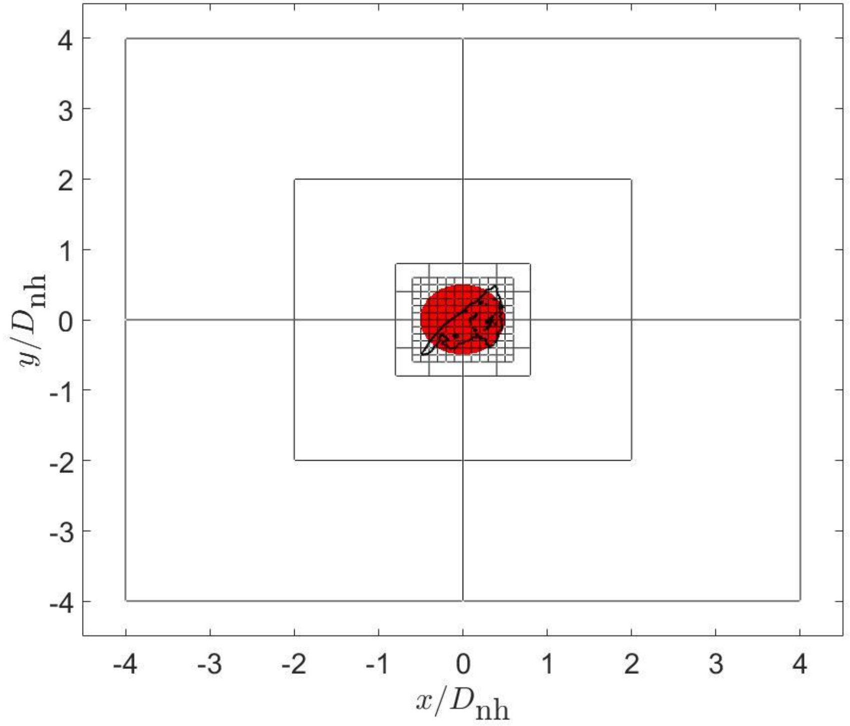
Results: LES cases and meso-scale model grids

LES of surface heterogeneities:
- Case 1: Circular constant
- Case 2: Circular random
- Case 3: Downscaled Yatir forest



Six investigated grid resolutions (different meso-scale model grids):

- $\Delta x = 0.1 \times D_{\mathrm{nh}}$
- $\Delta x = 0.2 \times D_{\mathrm{nh}}$
- $\Delta x = 0.4 \times D_{\mathrm{nh}}$
- $\Delta x = 0.8 \times D_{\mathrm{nh}}$
- $\Delta x = 2.0 \times D_{\mathrm{nh}}$
- $\Delta x = 4.0 \times D_{\mathrm{nh}}$



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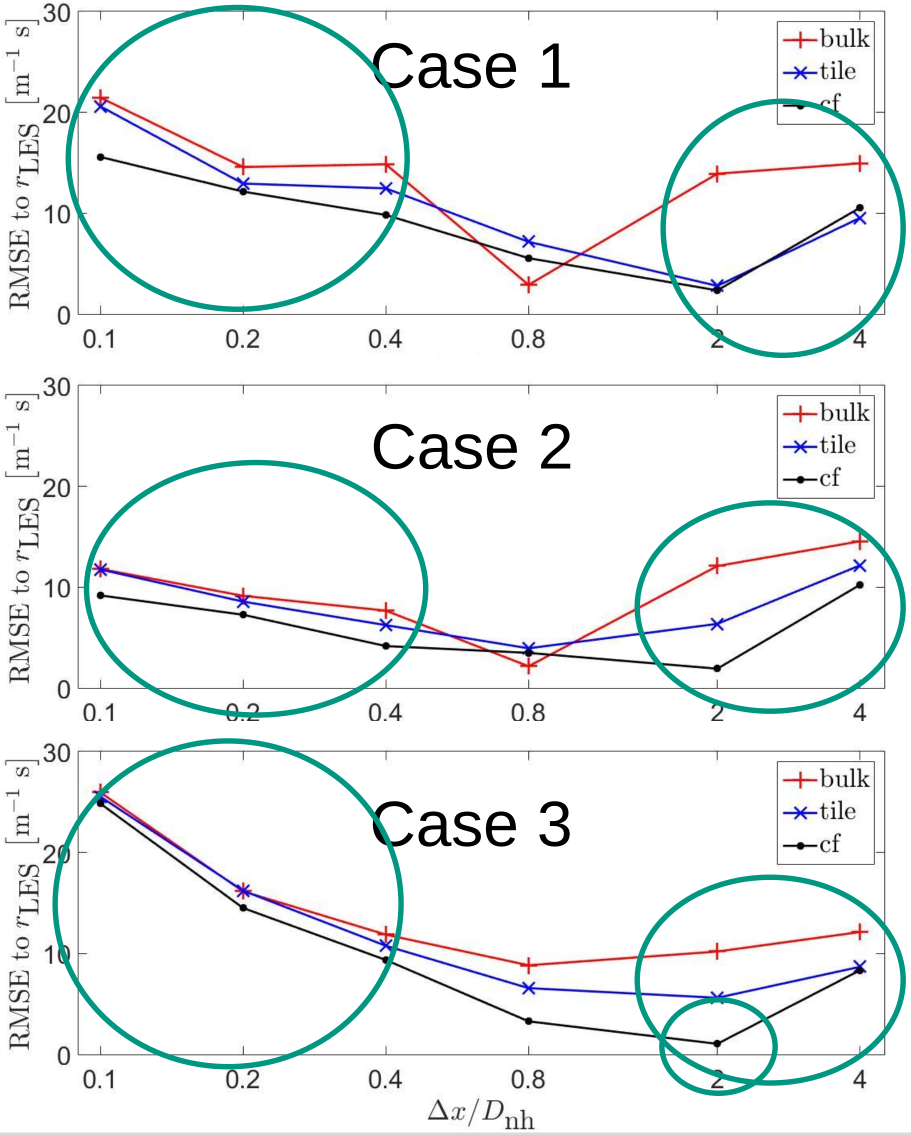
Results: Root-mean-square error (RMSE) plots

Findings:

- Mainly $\mathrm{RMSE_{cf}} < \mathrm{RMSE_{tile}} < \mathrm{RMSE_{bulk}}$
- For small Δx:
  - $\mathrm{RMSE_{case1}} > \mathrm{RMSE_{case2}}$
  - $\mathrm{RMSE_{case3}}$ largest
- For large Δx:
  - Errors of same size
  - Errors approach each other for $\Delta x = 4 \times D_{\mathrm{nh}}$
- $\mathrm{RMSE_{cf}}$ smallest in most heterogeneous case



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Summary & Conclusions

- Analytic derivation of subgrid-scale aerodynamic resistance parametrization from covariance-function approaches

  → correction factors to bulk similarity
- Correction factors depend on meso-scale model grid and heterogeneity map χ.
- Comparison of r_{cf} against r_{bulk} & r_{tile} (reference r_{LES}) for three test cases of surface heterogeneities (circular constant, circular random, Yatir forest)
- Covariance function approach shows smaller deviations from LES than bulk and tile approaches.
- Future work:
  - Calculation of χ from satellite data for realistic applications (here χ from input maps for LES)
  - Investigation of advection and flux divergence contributions

Thanks for your attention!!