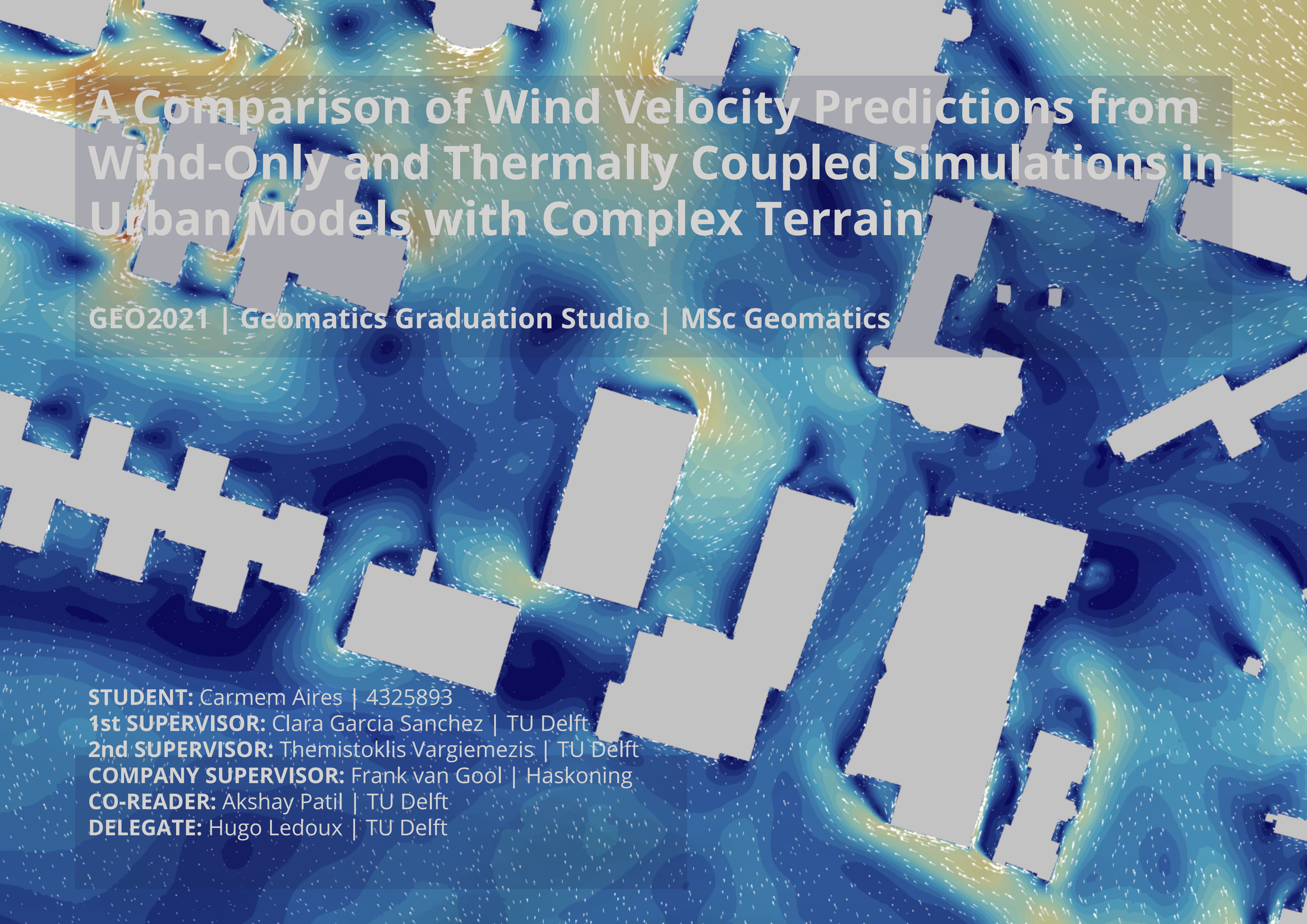

A Comparison of Wind Velocity Predictions from Wind-Only and Thermally Coupled Simulations in Urban Models with Complex Terrain

GEO2021 | Geomatics Graduation Studio | MSc Geomatics

STUDENT: Carmem Aires | 4325893
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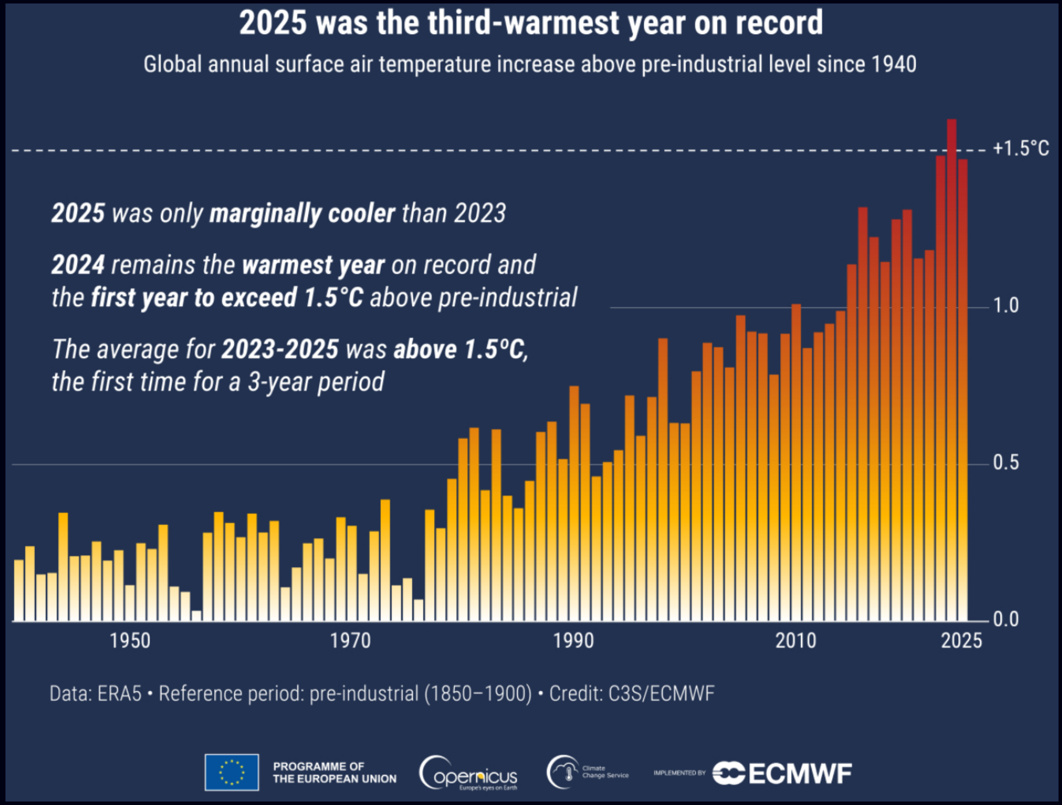
COMPANY SUPERVISOR: Frank van Gool | Haskoning
CO-READER: Akshay Patil | TU Delft
DELEGATE: Hugo Ledoux | TU Delft

CONTENT

INTRODUCTION

- Frequency, duration and intensity of **heatwaves** will more and more increase (IPCC, 2023).
- Most of the global population is **living in cities**, where dense built environment tends to amplify temperatures
- So more and more people are exposed to **heat-related health risks (**WHO, 2024**)**



Source: Copernicus Climate Change Service (C3S)

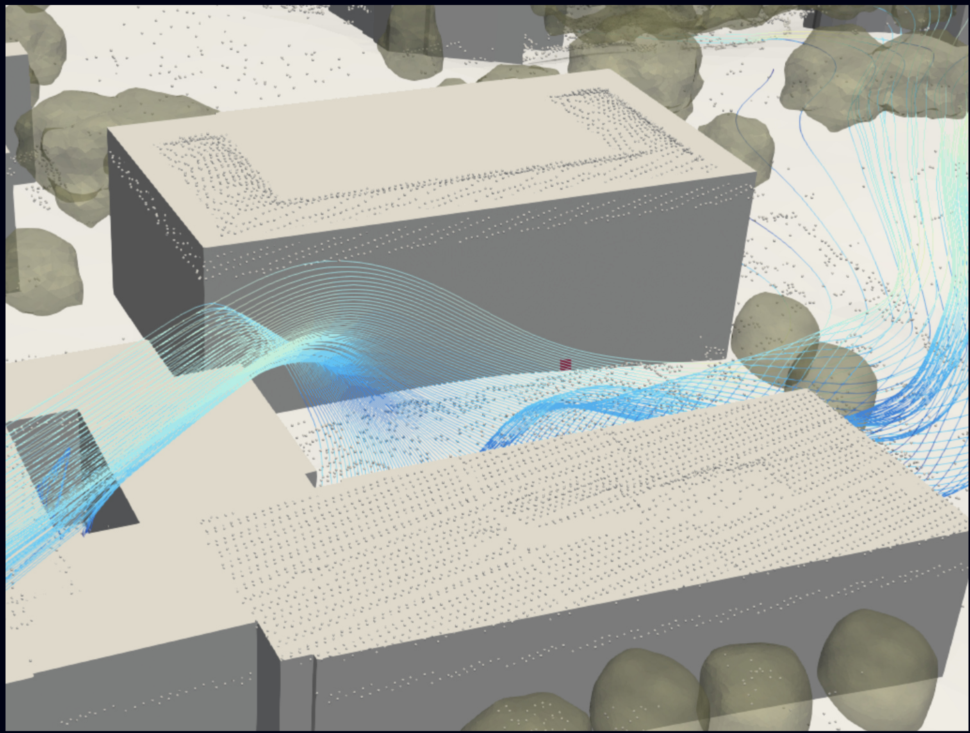
INTRODUCTION

In this context, UN-HABITAT highlights the importance of closing **urban climate data gaps** to enable evidence-based decision-making and attract investment

UN-Habitat - The United Nations Human Settlements Programme

↓

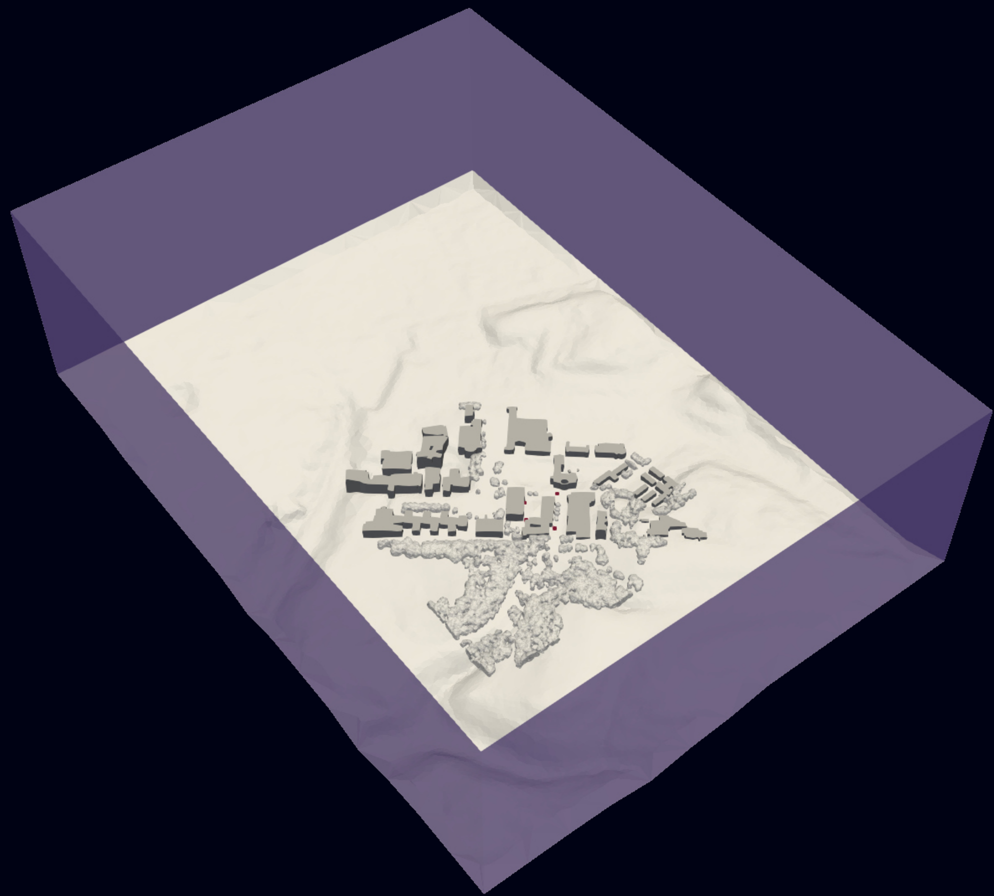
Urban Microclimate CFD studies can support closing these gaps



URBAN MICROCLIMATE CFD

Computational method to solve meteorological microclimate phenomena (e.g. turbulence, wakes, thermals).

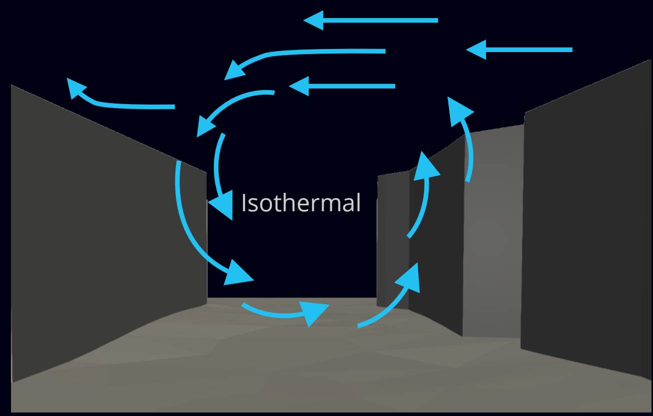
- within 2km-5km
- Using a 3D model of the air and solids



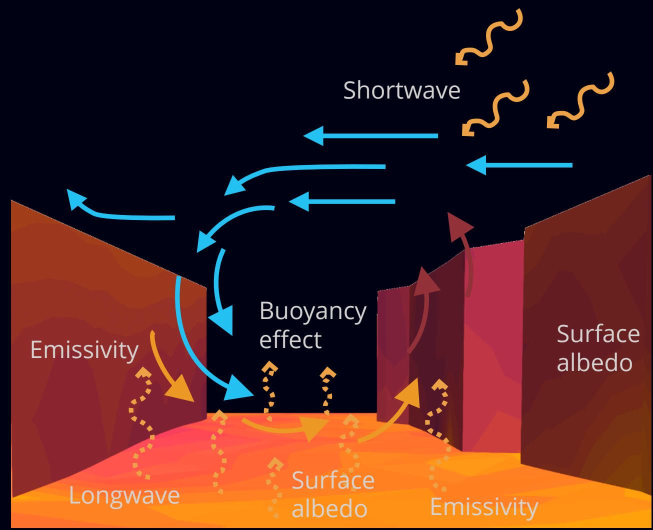
URBAN MICROCLIMATE CFD STUDIES

Two groups of studies

Treating the atmosphere as Isothermal (wind-only)



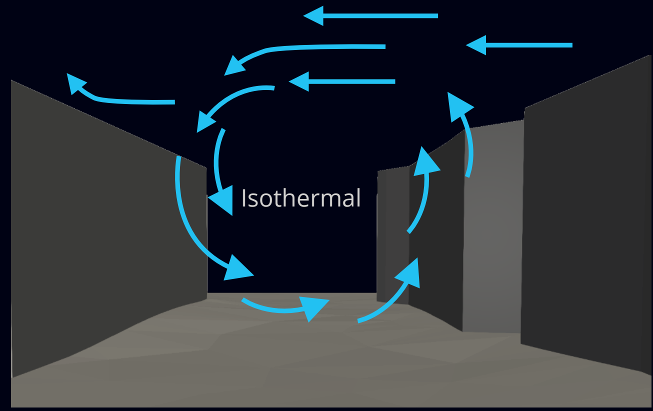
Treating the atmosphere as Non-Isothermal (Thermally coupled)



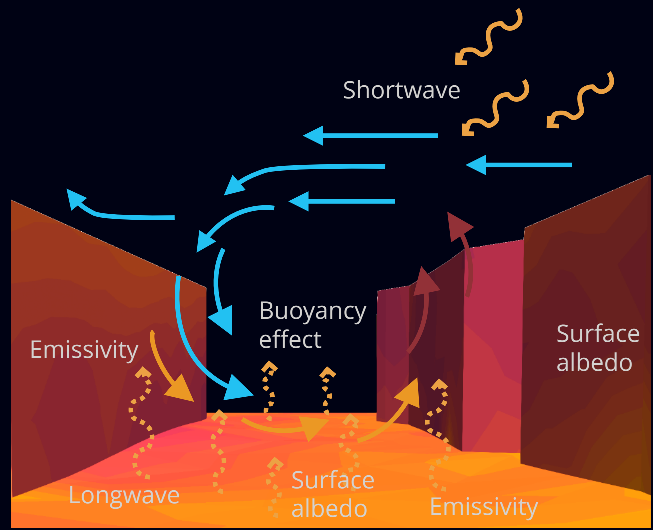
STATE OF THE ART - STUDIES

The majority of CFD studies treats the atmosphere as **isothermal**

… however, this assumption loses **validity during extreme heat events and calm summer days**



Isothermal Case
(wind-only)

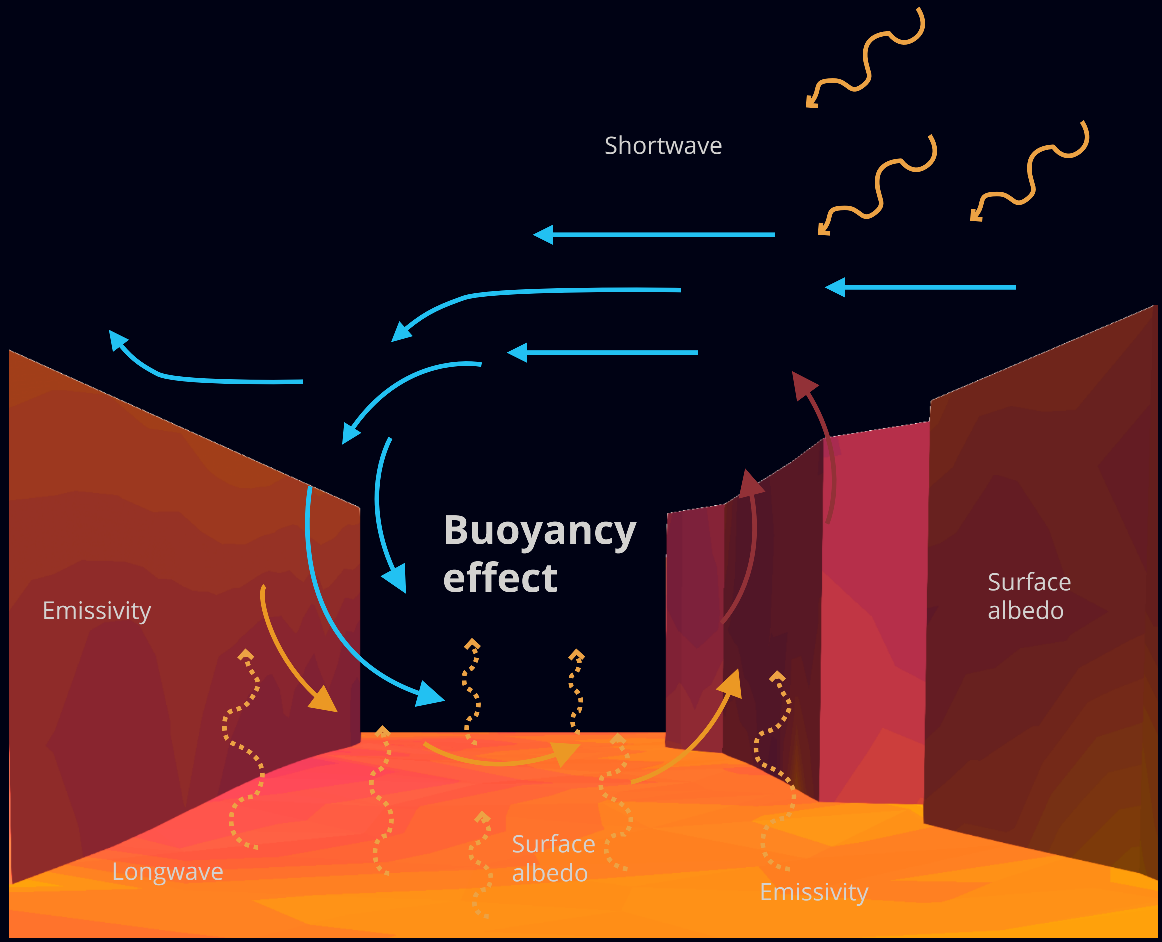


Non-Isothermal Case
(Thermally coupled)

BUOYANCY FORCING

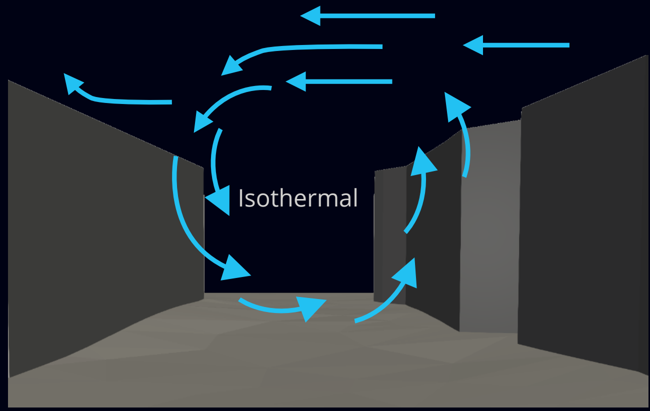
Effect generated by **hot urban surfaces (heated by solar gains or man-made heat)**

Warm air rises and cool air sinks.

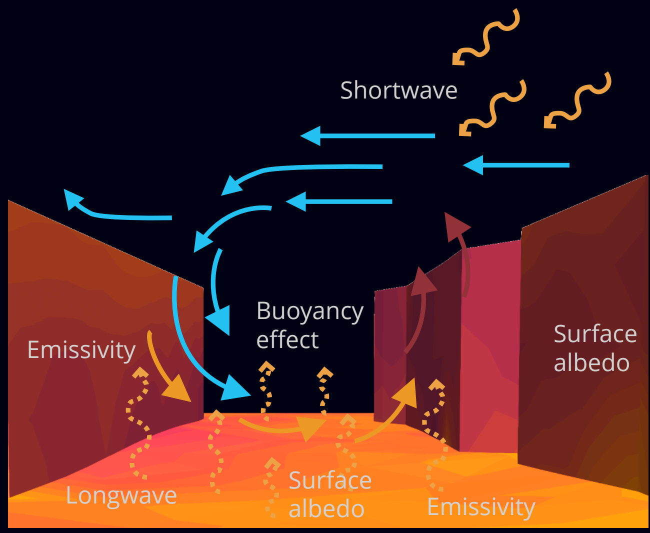


STATE OF THE ART - SOLVERS

simpleFoam (SF) wind only



urbanMicroclimateFoam (uMF) is an open-source solver offering the missing multiphysics formulations (Kubilay et al., 2017)



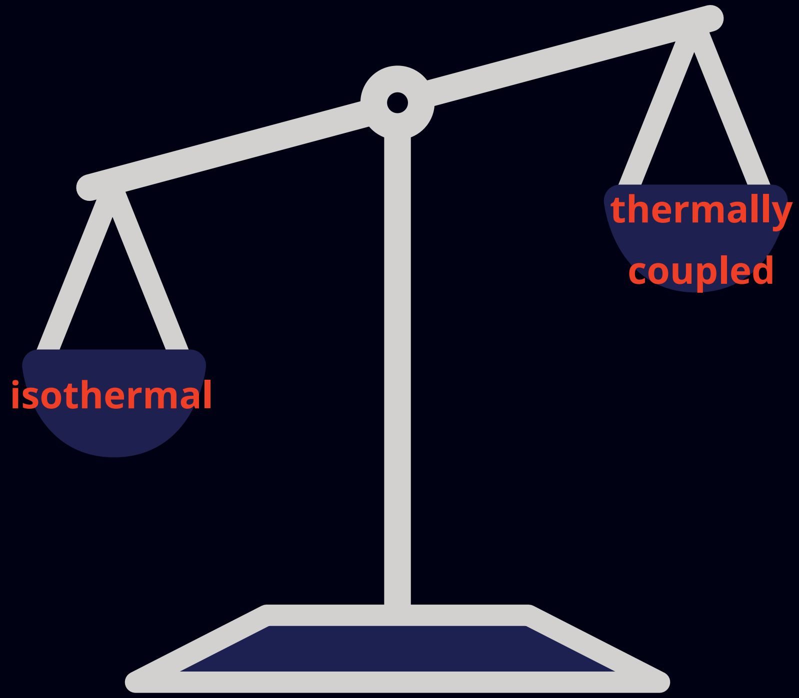
RESEARCH GAPS AND OBJECTIVES

It is unclear under which conditions **wind-only simulations would be sufficient**

↓

Compare simulation types

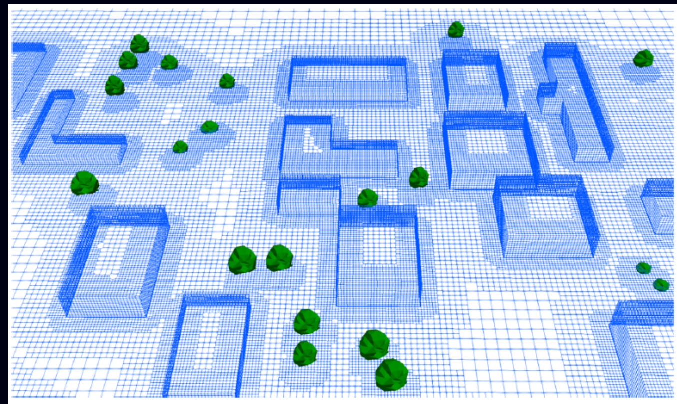
when buoyancy is non-negligible



RESEARCH GAPS AND OBJECTIVES

published applications of uMF to realistic urban models including **complex geometry, especially terrain are scarce**

Evaluate the **feasibility of urbanMicroclimateFoam** when applied to a **realistic urban model with complex terrain**



Source: Rahimi et. al., 2025

RESEARCH QUESTIONS

1. How feasible is the **application of urbanMicroclimateFoam to realistic urban models** that include non-flat terrain, given current geometric reconstruction and meshing tools?

2. How do mesh requirements, solver parameters, and **computational demands differ between urbanMicroclimateFoam and** the wind-only solver **simpleFoam** when applied to the same case study?

3. How do wind-speed predictions from **simpleFoam** compare to those of **urbanMicroclimateFoam** when both are evaluated against field measurements from four stations over a one-hour window under a single inflow condition during a representative heatwave?

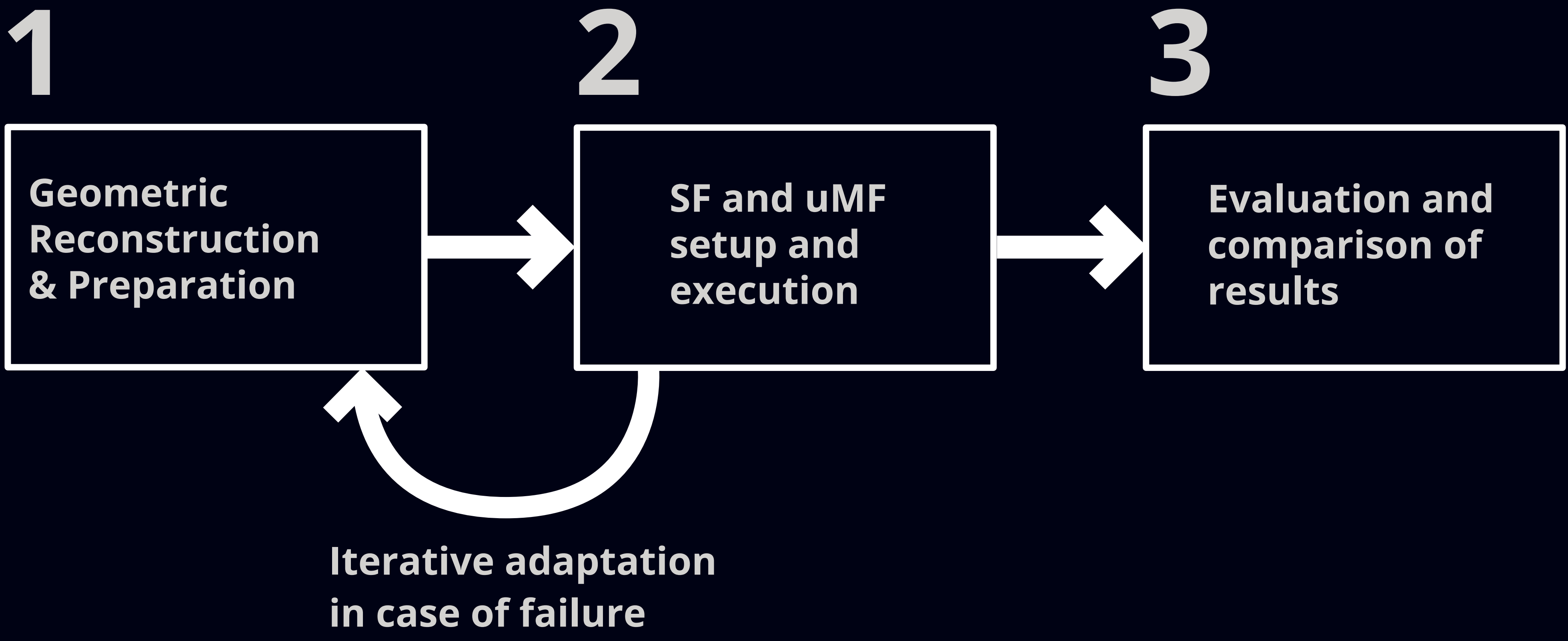
RESEARCH CASE-STUDY

Carnegie Mellon University campus in Pittsburgh - US

- Meteorological Observations during a heatwave in 2024 - MORICHI
- detailed geospatial data (point clouds, polygons)
- pronounced terrain variation (83m)

RESEARCH CASE-STUDY

METHODOLOGY



METHODOLOGY

1

Geometric Reconstruction & Preparation

1.1 Input data Pre-processing →

1.2 Surface Mesh Reconstruction →

1.3 Mesh / Radiation preparation

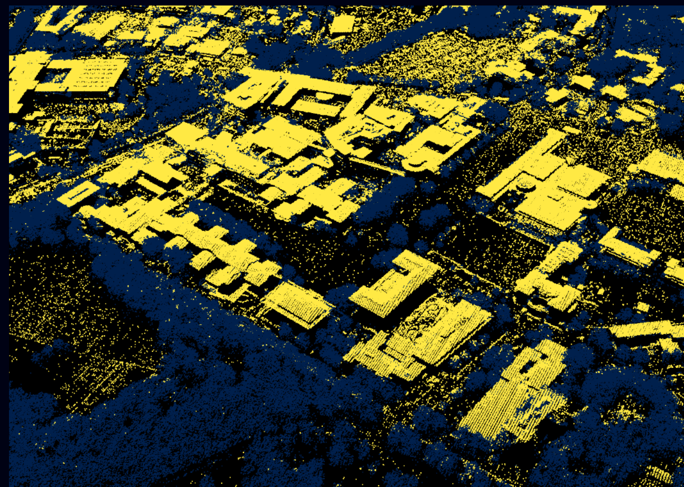
INPUT DATA PREPROCESSING

1

Geometric Reconstruction & Preparation

1.1

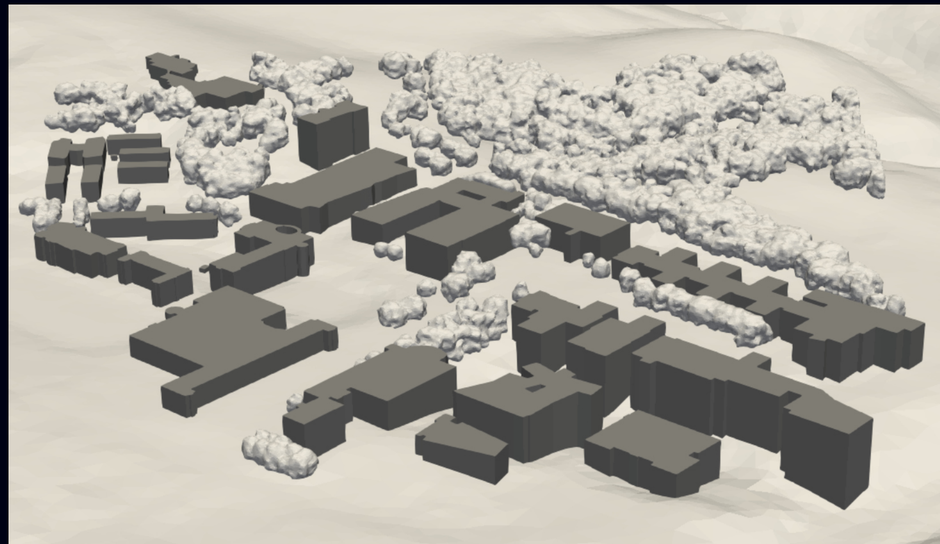
Input data Pre-processing



GEOMETRIC RECONSTRUCTION

1

Geometric Reconstruction & Preparation



1.1

Input data Pre-processing

→

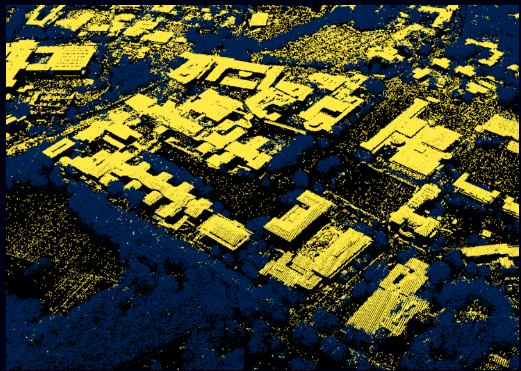
1.2

Surface Mesh Reconstruction

GEOMETRIC RECONSTRUCTION

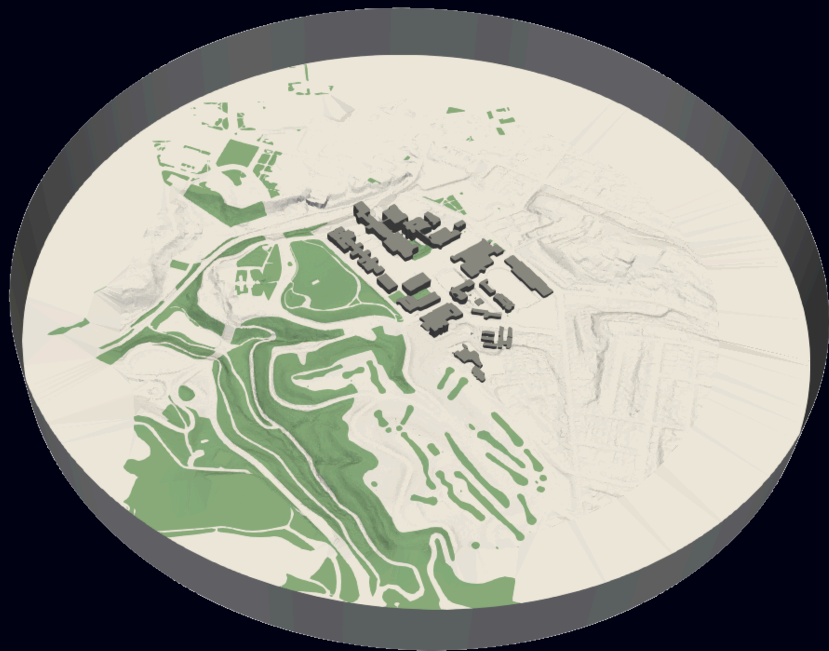
Automated pipelines exist to build base models (City4CFD)

Point-clouds



2D geometry

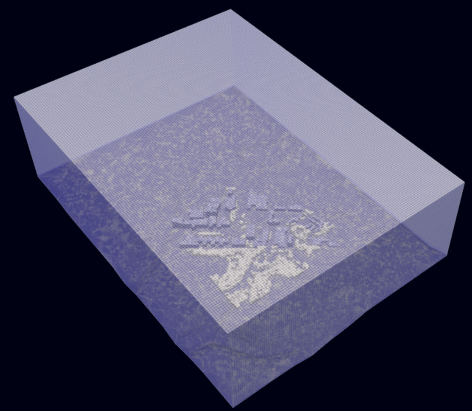
Simulation ready 3D model

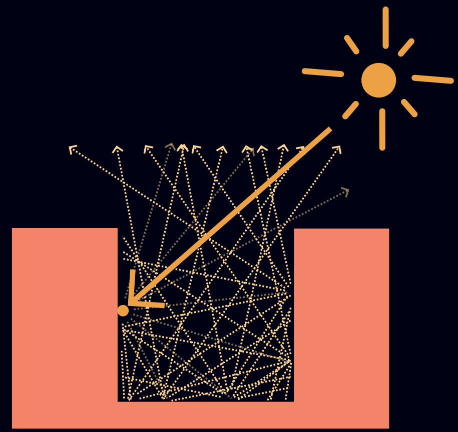


PREPARATION STEPS

1

Geometric Reconstruction & Preparation





1.1

Input data Pre-processing

→

1.2

Surface Mesh Reconstruction

→

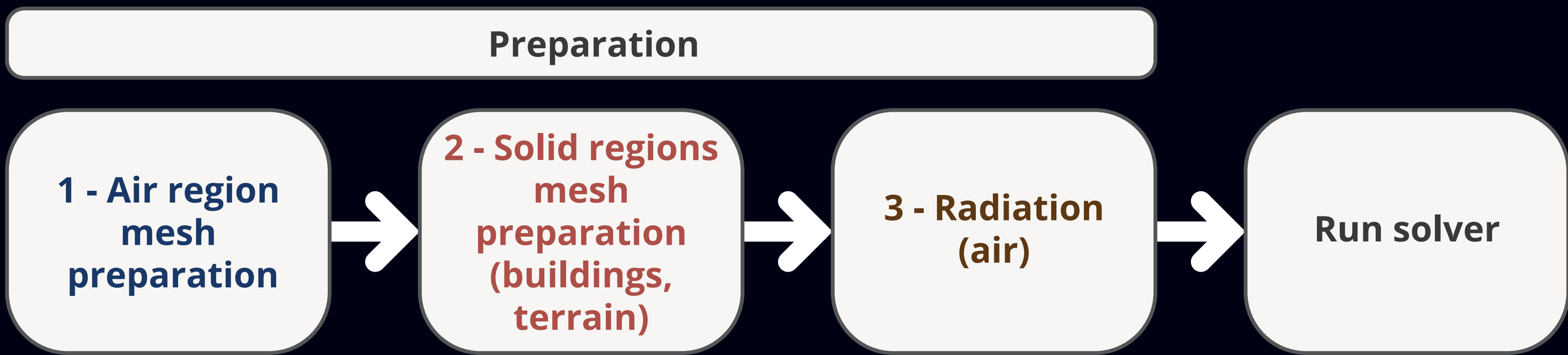
1.3

Mesh / Radiation preparation

PREPARATION STEPS

SimpleFoam - wind-only

urbanMicroclimateFoam - multiphysics

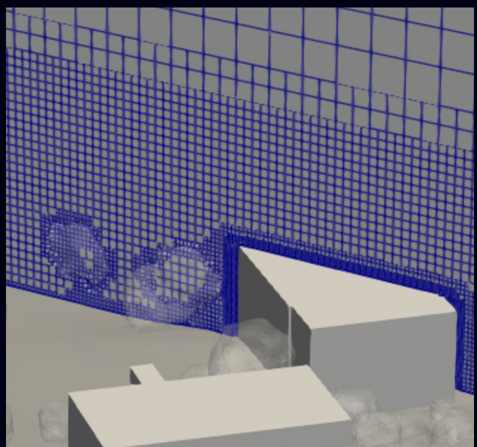


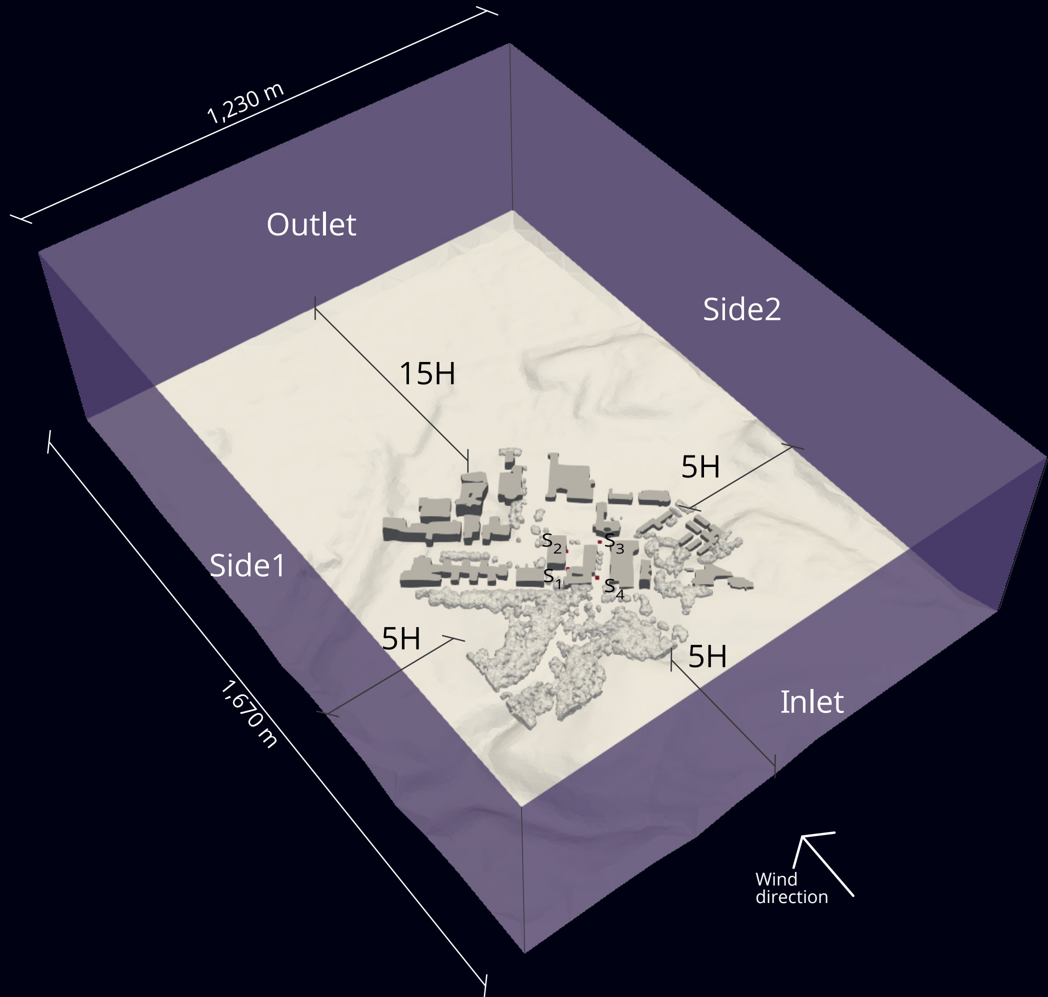
MESH CONSTRUCTION

1.3

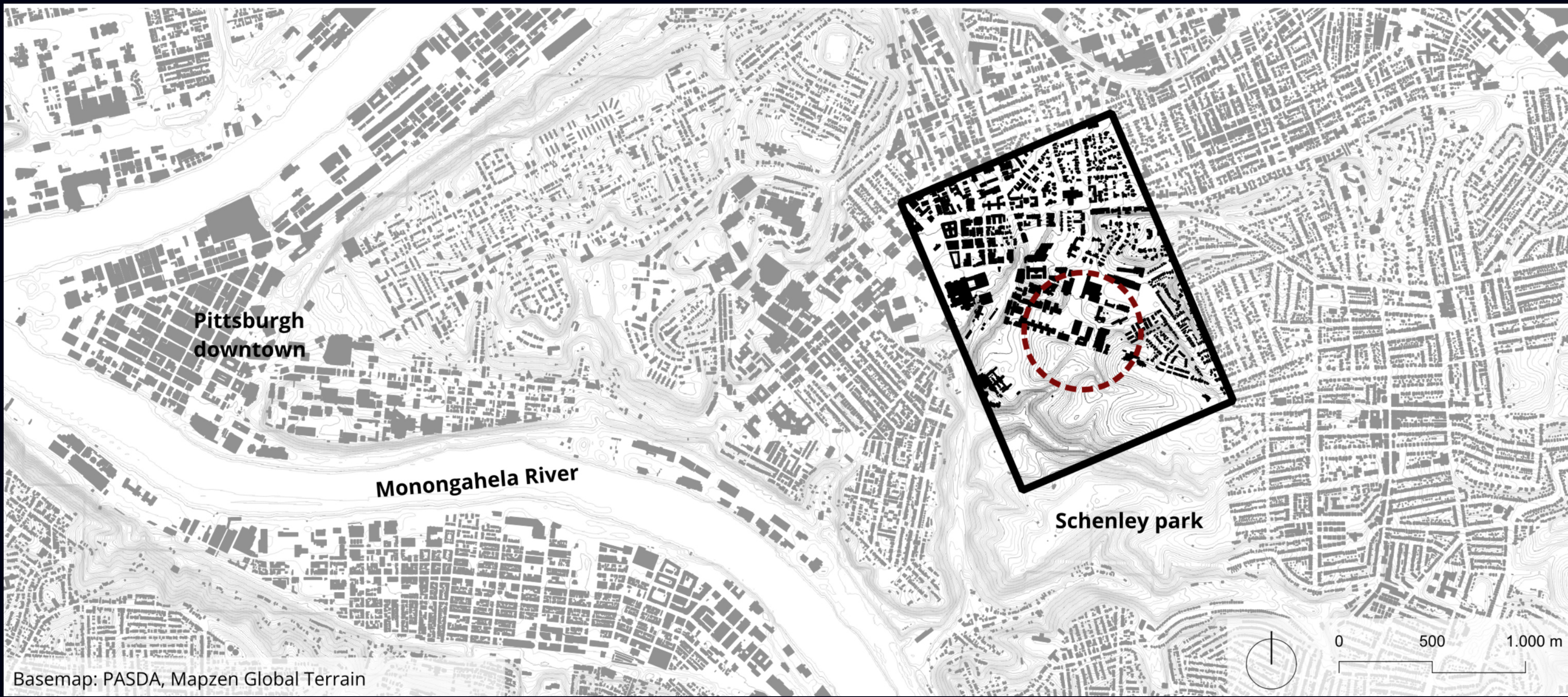
1 - Air region mesh preparation

- COST732 guidelines domain size
- 16 Million cells





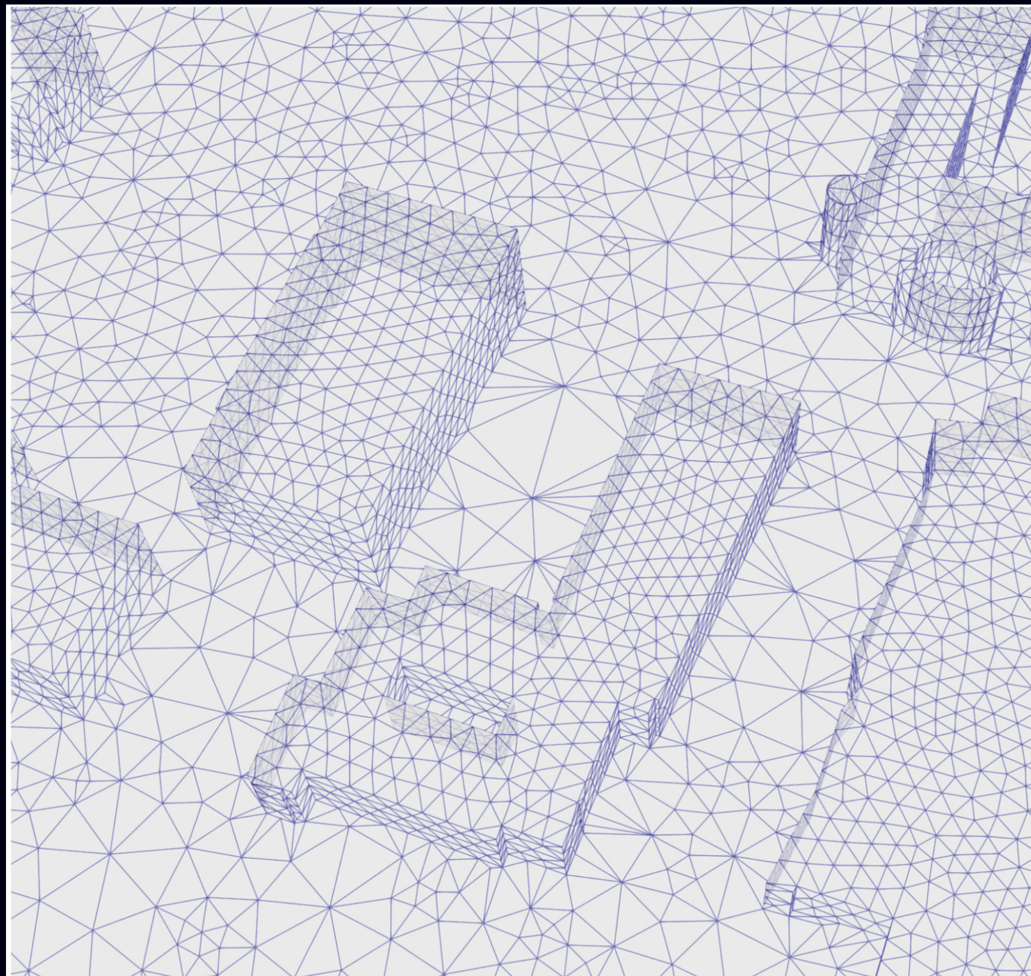
MESH CONSTRUCTION



RESULTING MESHES

1.3

2 - Solid regions - mesh preparation (buildings, terrain)



RADIATION PREPARATION

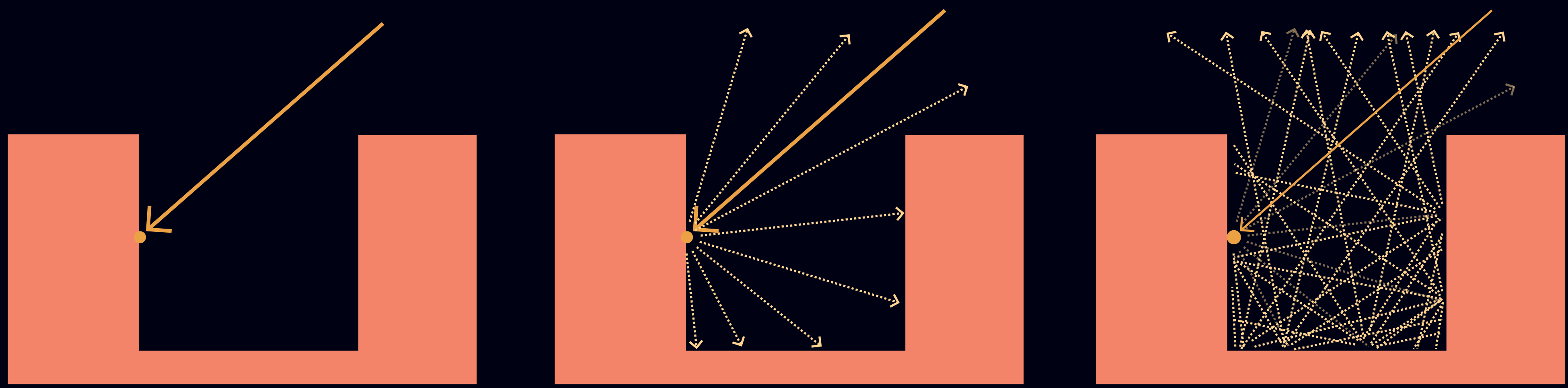
1.3

3 - Radiation preparation (air)

Ray tracing

Incoming sun light

Surface thermal radiation



Source: Oke, 2017.

METHODOLOGY

1

Geometric Reconstruction & Preparation

→

2

SF and uMF setup and execution

MODEL SETUP CRITERIA

2

SF and uMF setup and execution

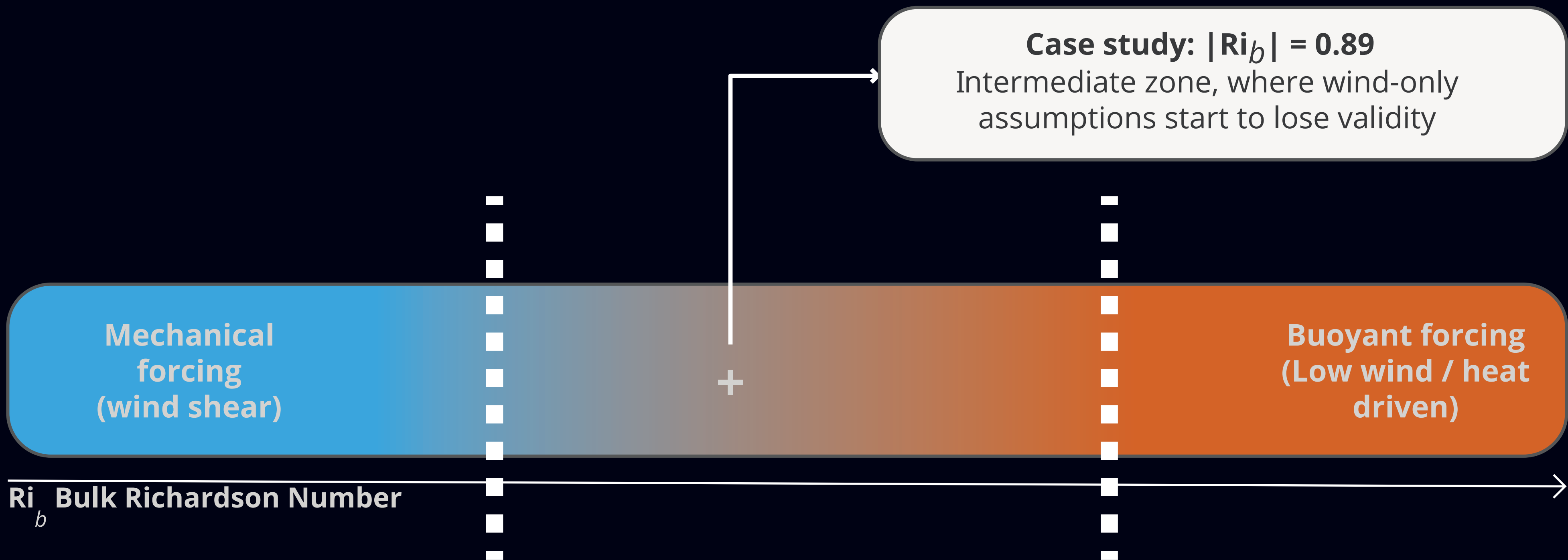
Criteria:

- Hottest day (MORICHI, 2025)
- Minimal wind-direction variability (Iowa Environmental Mesonet ASOS stations, 2026).

Time window

- 27th August 2024
- 13:00 to 14:00
- Inflow 157° azimuth
- 1.6 m/s

MODEL SETUP



|Ri_b| > 0.2

$$Ri_b = \frac{g\,H\,(\theta_a - \theta_g)}{\theta_a\,u_a^2},$$

|Ri_b| > 2.0

Buoyancy becomes non-negligible
Mei and Yuan, 2022

Canyon vortex restructuring
Mei and Yuan, 2022

METHODOLOGY

1

Geometric Reconstruction & Preparation

→

2

SF and uMF setup and execution

→

3

Evaluation and comparison of results

PERFORMANCE ASSESSMENT & VALIDATION

3

Evaluation and comparison of results

- Wind speed comparison: **Dimensionless statistical indicators** recommended by Sabatino et al. (2011), Chang and Hanna (2004)

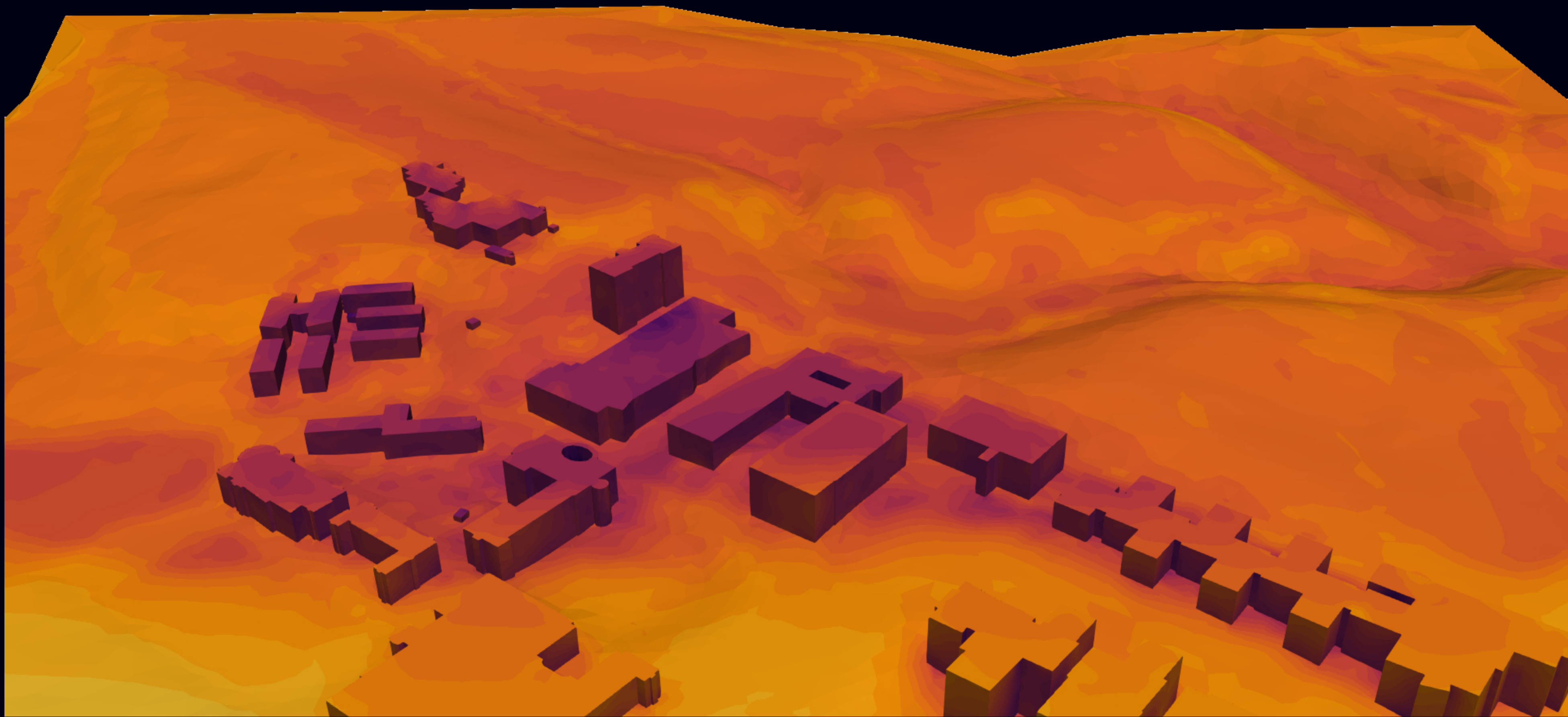
RESULTS

RESEARCH QUESTION 1

Feasibility of **urbanMicroclimateFoam** to **realistic urban models** with **terrain**

RESEARCH QUESTION 1

Achievable...



RESEARCH QUESTION 1

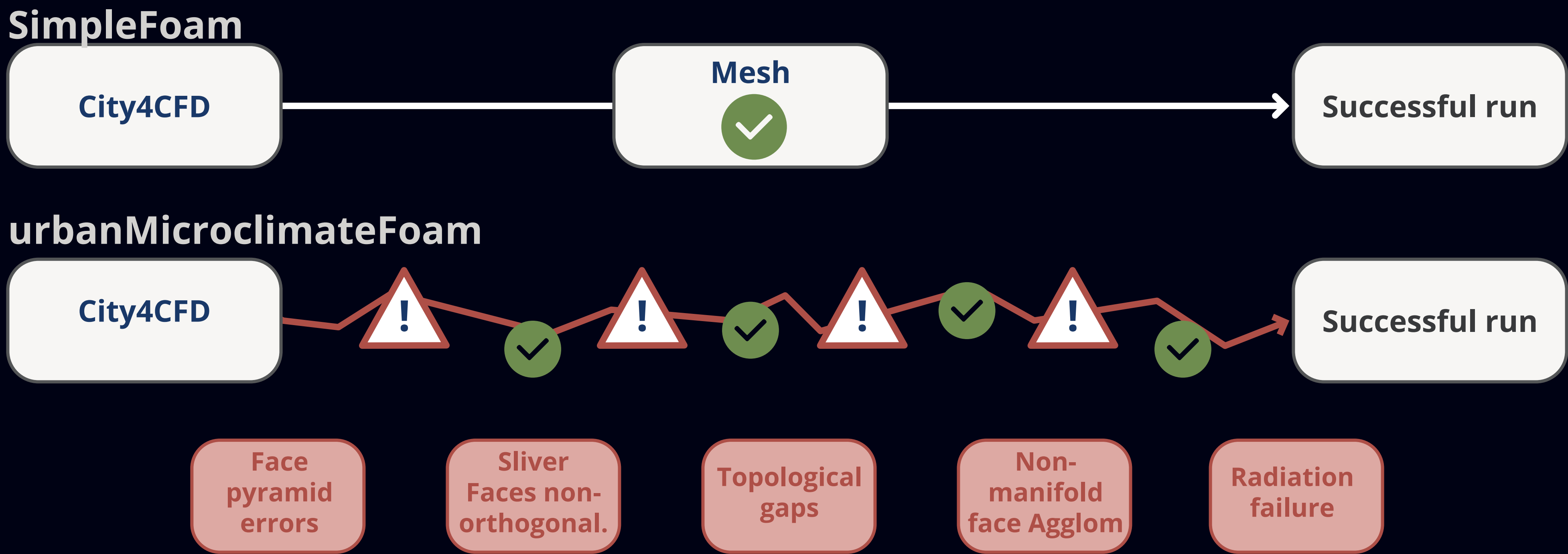
...however, it is subject to **several constraints.**

FEASIBILITY OF APPLICATION

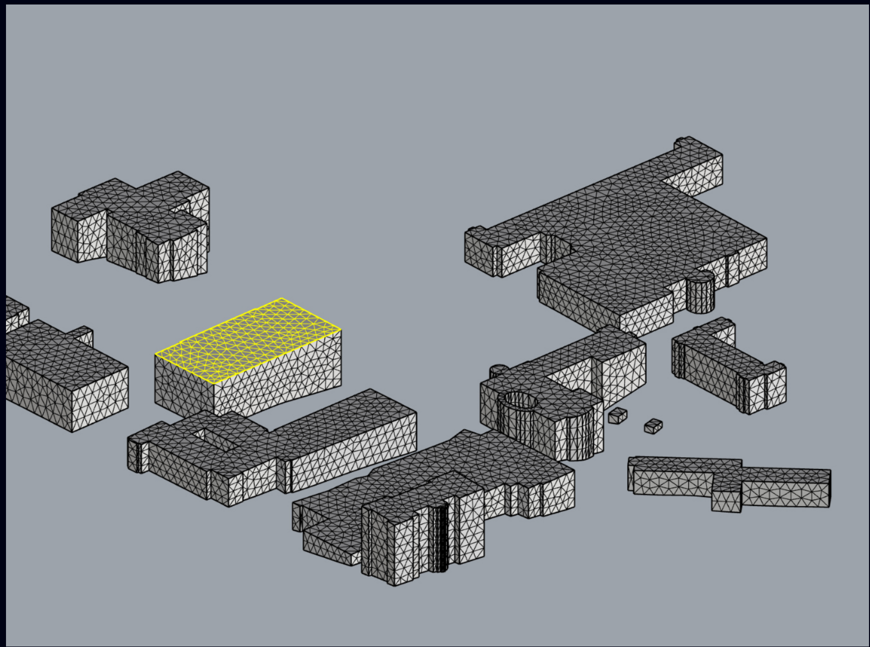
The model that performed well in SF...

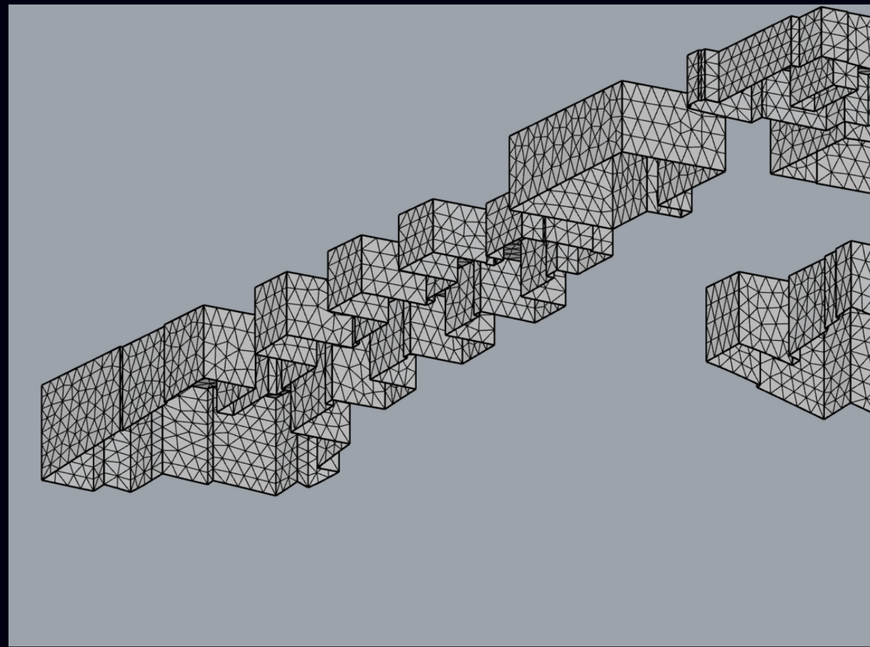
FEASIBILITY OF APPLICATION

… could not be used directly with uMF; **the transition required progressive adaptation** of the geometry to achieve numerical stability.



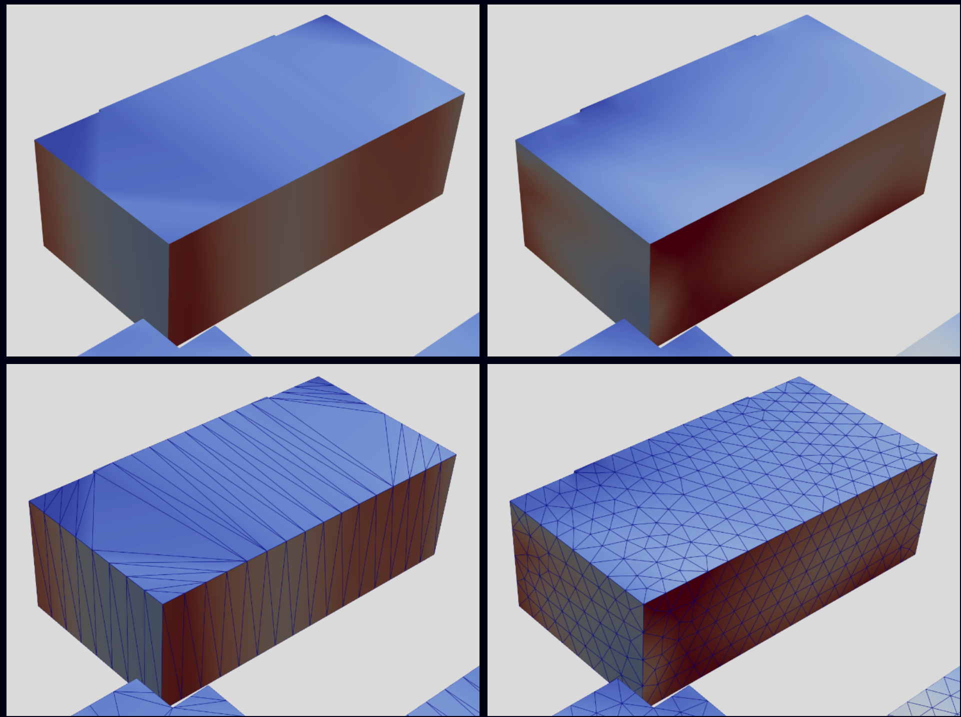
FEASIBILITY OF APPLICATION





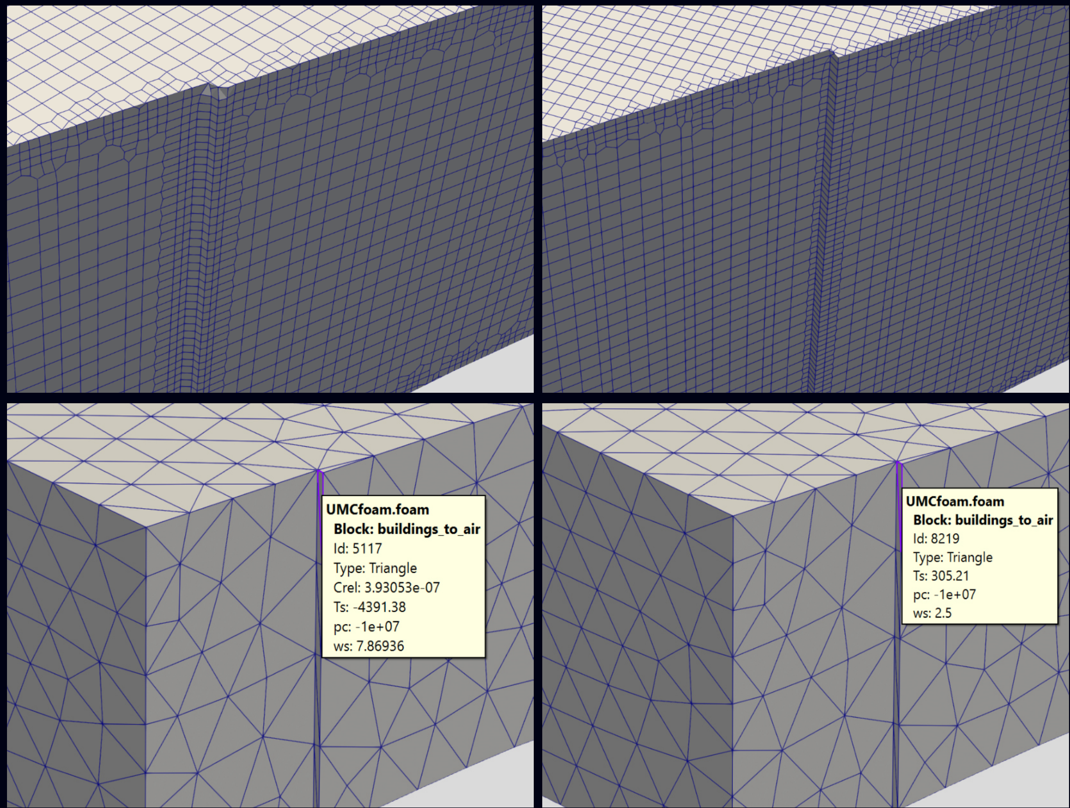
Separation of surfaces, removal of bottom faces and party walls for the radiation step

FEASIBILITY OF APPLICATION



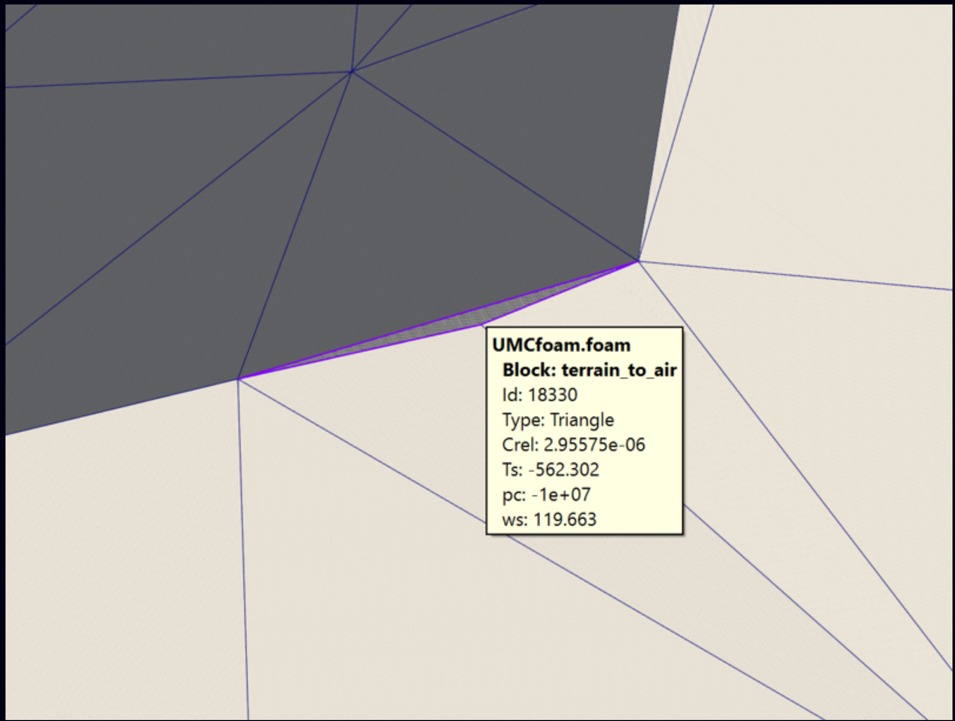
Mesh refinement to refine results and avoid instability

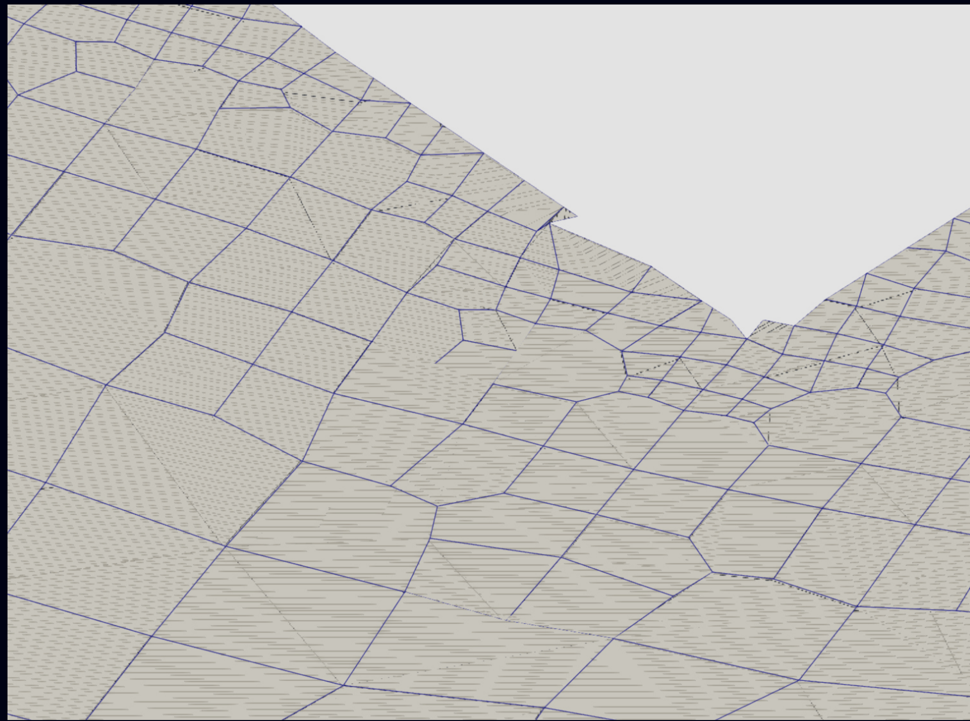
FEASIBILITY OF APPLICATION



Finer cells to avoid numerical instability

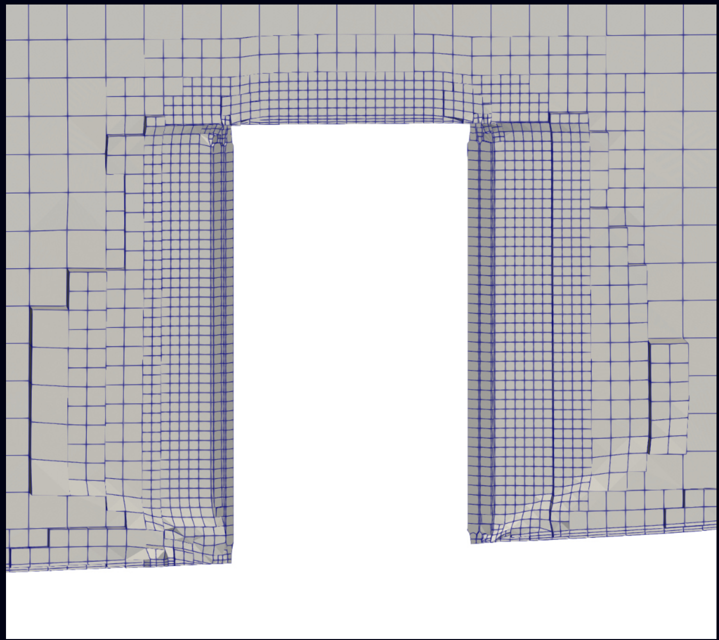
FEASIBILITY OF APPLICATION

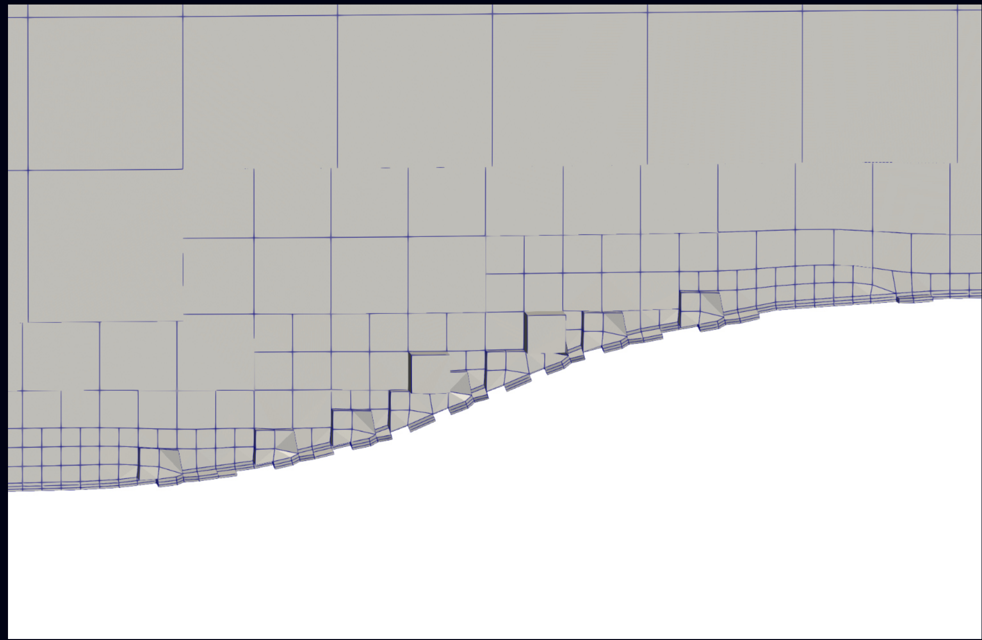




Finer cells to avoid numerical instability

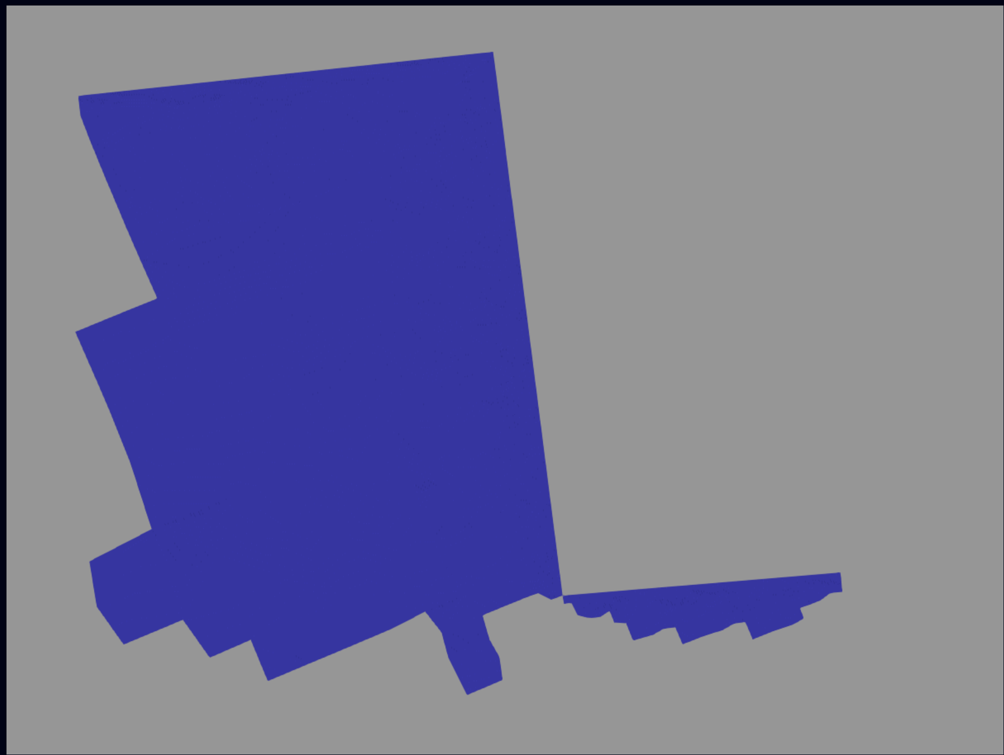
FEASIBILITY OF APPLICATION





Existing imperfections (non-orthogonality) in the mesh can break the **faceAgglomerate** algorithm's capacity of finding neighbouring faces

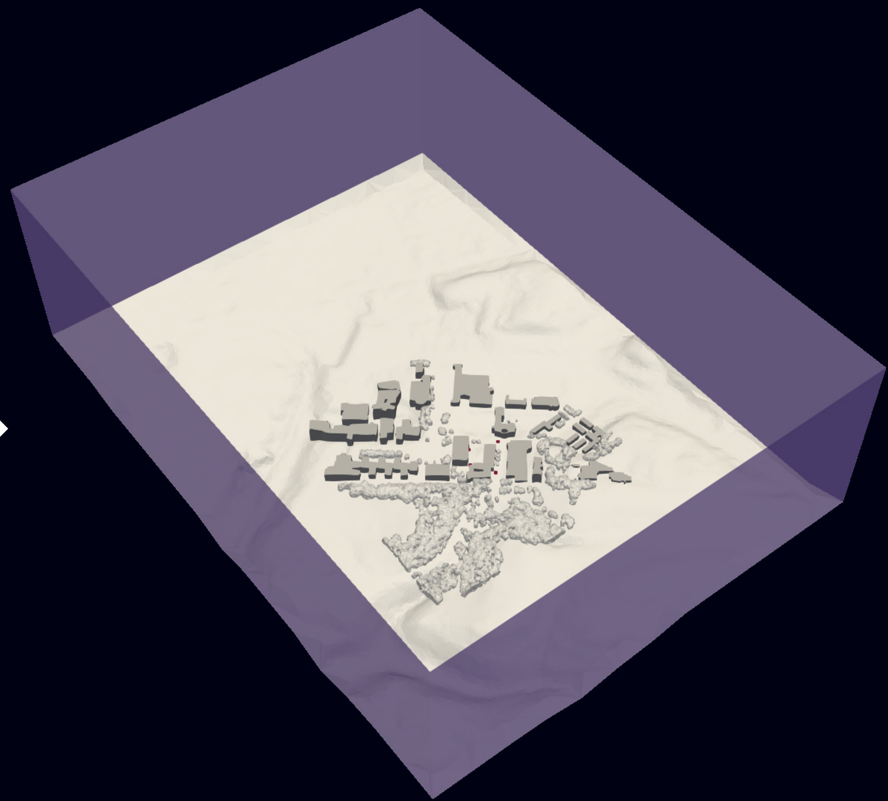
FEASIBILITY OF APPLICATION



faceAgglomerate can create non-manifold agglomeration (viewFactorsGen step fail)

FEASIBILITY OF APPLICATION

Boundary conditions formulations
not adaptable to circular domains



Constrained to one direction

FEASIBILITY OF APPLICATION

Together, these preprocessing steps are very time demanding, consuming most of the preparation and setup time.

RESEARCH QUESTION 2

Time and **computational demand** differences

On identical geometry and 20 cores, uMF took 3.6× longer than SF (6 h 28 min versus 1 h 49 min)

COMPUTATIONAL DEMANDS

1. Additional physics

2. “Hidden” reasons:

   Mesh requirements
   - Finer cells

SimpleFoam

```
case/
├── 0/
│   └── Include/
│       └── ABLConditions
│   ├── U              # velocity
│   ├── p              # pressure
│   ├── nut            # turbulent kinematic viscosity
│   ├── k              # turbulent kinetic energy
│   └── epsilon        # dissipation rate
├── constant/
│   ├── polyMesh/
│   ├── transportProperties
│   └── turbulenceProperties
└── system/
    ├── blockMeshDict
    ├── controlDict
    ├── decomposeParDict
    ├── extrudeMeshDict
    ├── fvSchemes
    ├── fvSolution
    ├── meshQualityDict
    ├── snappyHexMeshDict
    └── surfaceFeaturesDict
```

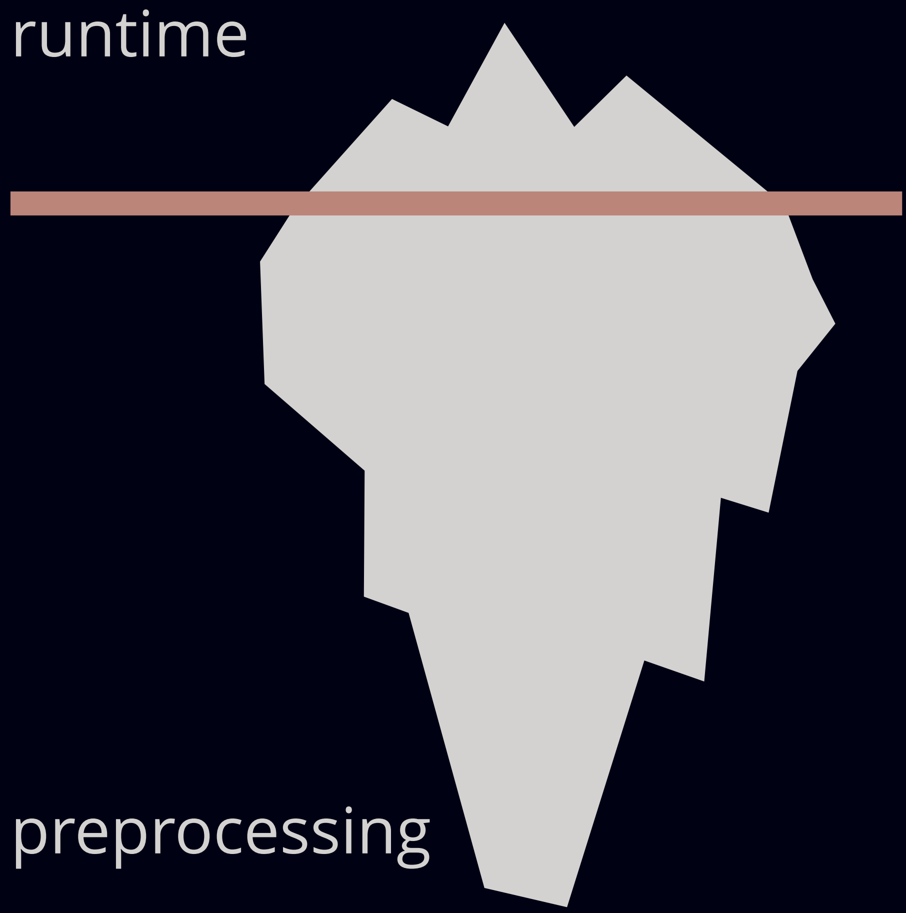
urbanMicroclimateFoam

```
case/
├── 0/
│   ├── air/
│   │   ├── alphat        # turbulent thermal diffusivity
│   │   ├── cloudCover    # hourly cloud cover
│   │   ├── epsilon       # turbulence dissipation rate
│   │   ├── gcr           # non-dimensional (rain)water mass flux
│   │   ├── k             # turbulence kinetic energy
│   │   ├── nut           # turbulent kinematic viscosity
│   │   ├── p             # pressure
│   │   ├── p_rgh         # modified pressure without hydrostatic effects
│   │   ├── qr            # net long-wave radiation
│   │   ├── qs            # net short-wave radiation
│   │   ├── T             # air temperature
│   │   ├── U             # wind velocity
│   │   ├── w             # humidity ratio
│   │   ├── Tambient      # air temperature reference values
│   │   ├── wambient      # humidity ratio reference values
│   │   └── include/
│   │       └── ABLConditions
│   │
│   └── buildings/
│   │   ├── Ts            # solid temperature
│   │   ├── ws            # solid moisture
│   │   └── pc            # capillary pressure (HAM)
│   │
│   └── terrain/
│   │   ├── Ts            # solid temperature
│   │   ├── ws            # solid moisture
│   │   └── pc            # capillary pressure (HAM)
│   │
│   └── vegetation/
│       ├── Ts            # solid temperature
│       ├── ws            # solid moisture
│       └── pc            # capillary pressure (HAM)
│
├── constant/
│   ├── air/
│   │   ├── polyMesh/                  # Air region mesh files
│   │   ├── g                          # Gravitational acceleration vector (0 0 -9.81)
│   │   ├── radiationProperties        # Long-wave radiation model settings (viewFactorSky)
│   │   ├── solarLoadProperties        # Short-wave solar radiation settings (directAndDiffuse)
│   │   ├── thermophysicalProperties   # Air thermophysical model (density, Cp, viscosity, EOS)
│   │   ├── turbulenceProperties       # Turbulence model selection (kEpsilon, realizableKE)
│   │   └── viewFactorsDict            # Face agglomeration settings for radiation view factors
│   │
│   ├── buildings/
│   │   ├── polyMesh/                  # Buildings solid mesh
│   │   ├── g                          # Gravitational acceleration vector (needed for moisture transport)
│   │   └── transportProperties        # Building material properties (rho, Cp, lambda, moisture
│   │                                  # retention curves), defines the HAM material model
│   │                                  # (e.g. Hamstad5Brick, AsphaltConcrete)
│   ├── terrain/
│   │   ├── polyMesh/
│   │   ├── g
│   │   └── transportProperties
│   │
│   ├── vegetation/
│   │   ├── polyMesh/
│   │   ├── g
│   │   └── transportProperties
│   │
│   ├── triSurface/
│   │   └── Mesh_Buildings.obj
│   │   └── Mesh_Terrain.obj
│   │   └── Mesh_Vegetation.obj
│   ├── regionProperties         # List of region types and names. Three types: fluid, solid and vegetation
│   ├── sunPosVector             # List of position of the sun for each timestep
│   ├── IDN                      # List of Direct Normal Irradiance (W/m²) for each timestep
│   └── Idif                     # List of Diffuse solar radiation (W/m²) for each timestep
│
└── system/
    ├── air/
    │   ├── changeDictionaryDict
    │   ├── createPatchDict
    │   ├── decomposeParDict
    │   ├── fvSchemes
    │   └── fvSolution
    │
    ├── buildings/
    │   ├── changeDictionaryDict
    │   ├── createPatchDict
    │   ├── decomposeParDict
    │   ├── fvSchemes
    │   ├── fvSolution
    │   └── setset.batch
    │
    ├── terrain/
    │   ├── changeDictionaryDict
    │   ├── createPatchDict
    │   ├── decomposeParDict
    │   ├── fvSchemes
    │   ├── fvSolution
    │   └── setset.batch
    │
    ├── vegetation/
    │   ├── changeDictionaryDict
    │   ├── createPatchDict
    │   ├── decomposeParDict
    │   ├── fvSchemes
    │   ├── fvSolution
    │   └── setset.batch
    │
    ├── blockMeshDict
    ├── controlDict
    ├── fvSchemes
    ├── fvSolution
    ├── meshQualityDict
    ├── snappyHexMeshDict
    └── surfaceFeaturesDict
```

COMPUTATIONAL DEMANDS

The time cost remains within the **same order of magnitude as SF.** It does not represent a barrier to the usage of the solver.

The barriers identified in RQ1, manual geometric correction, trial-and-error pre-processing, **consume far more time in the study**



RESEARCH QUESTION 3

Wind-speed predictions comparison

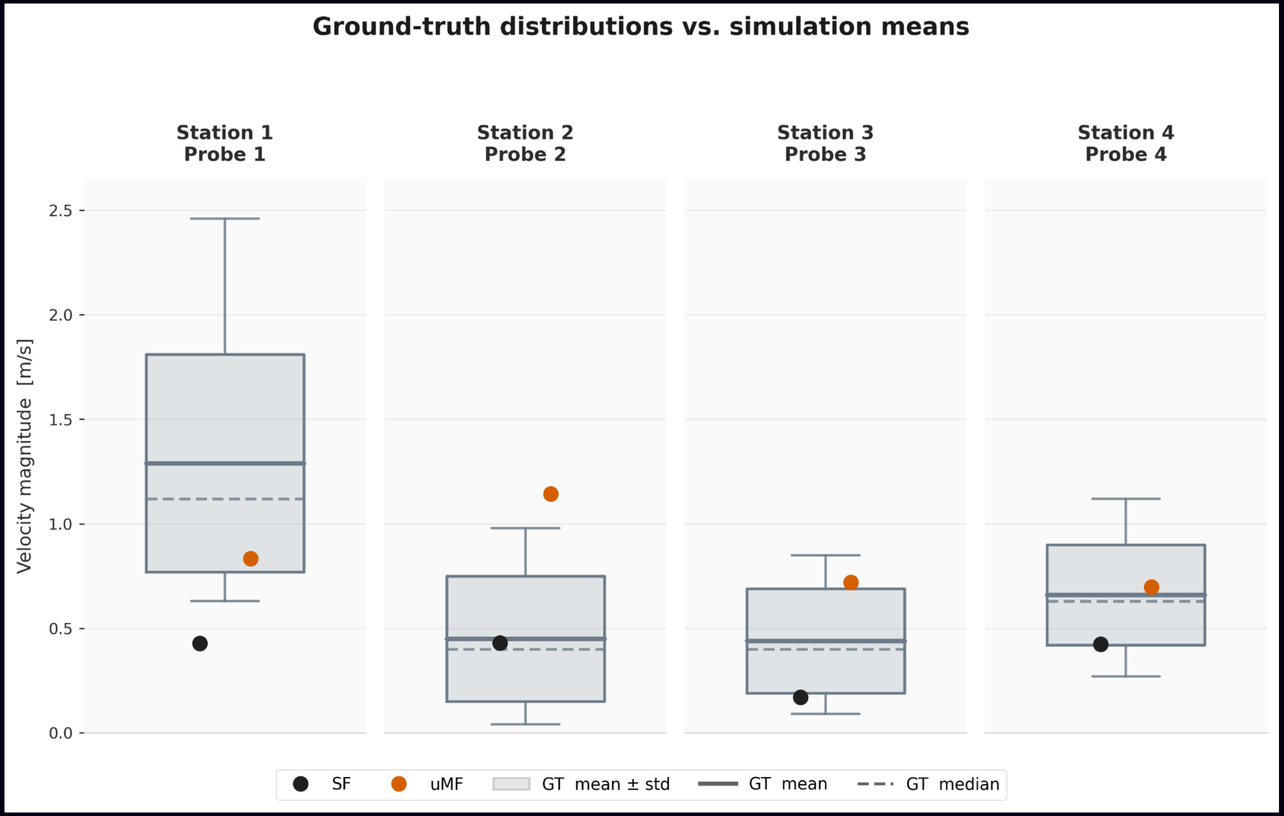
RESEARCH QUESTION 3

Wind-speed predictions comparison

In the regime studied here, uMF improved wind-speed predictions over SF.

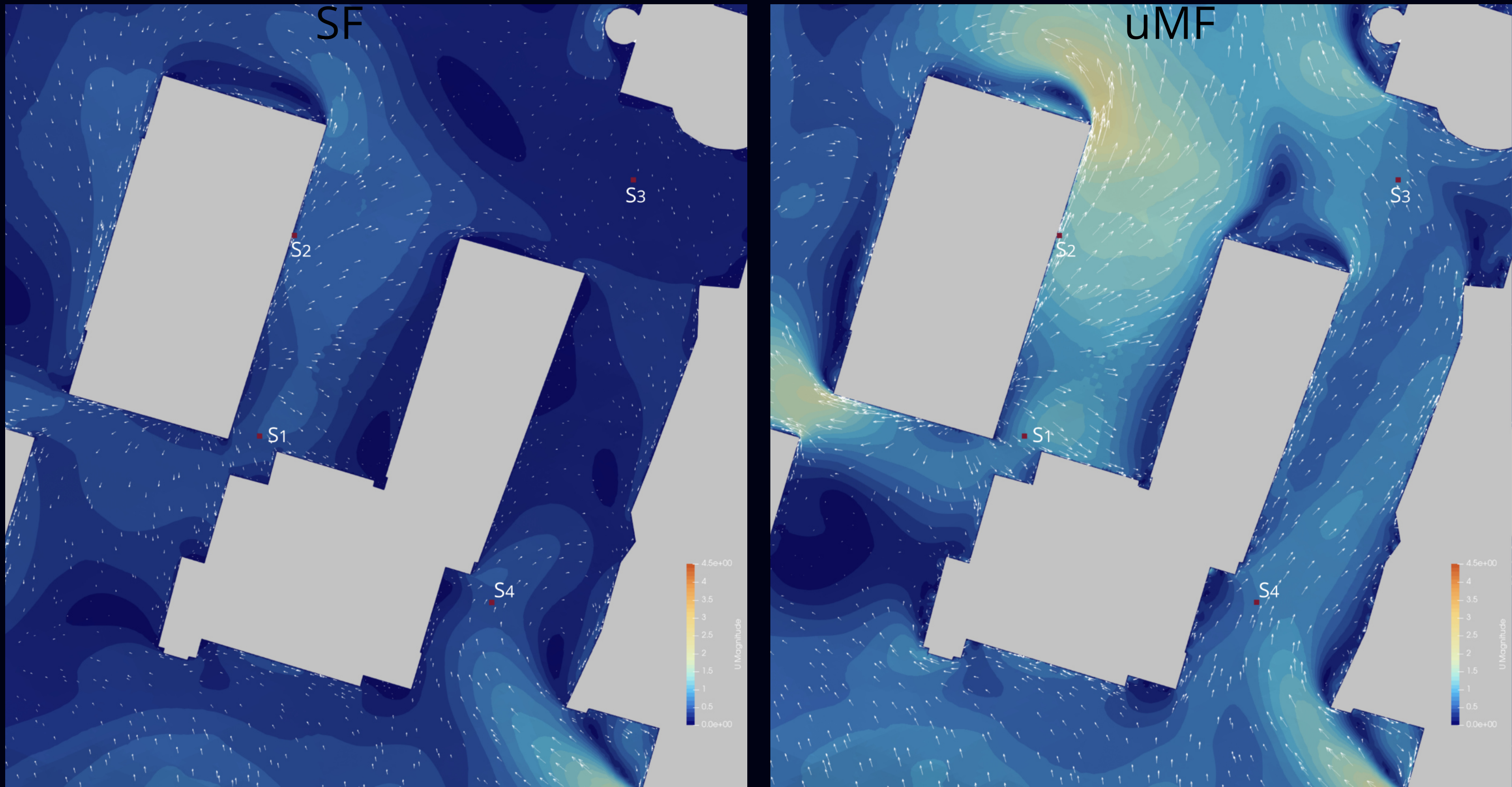
WIND-SPEED PREDICTION COMPARISON

Average improvement of 71% from SF to uMF .



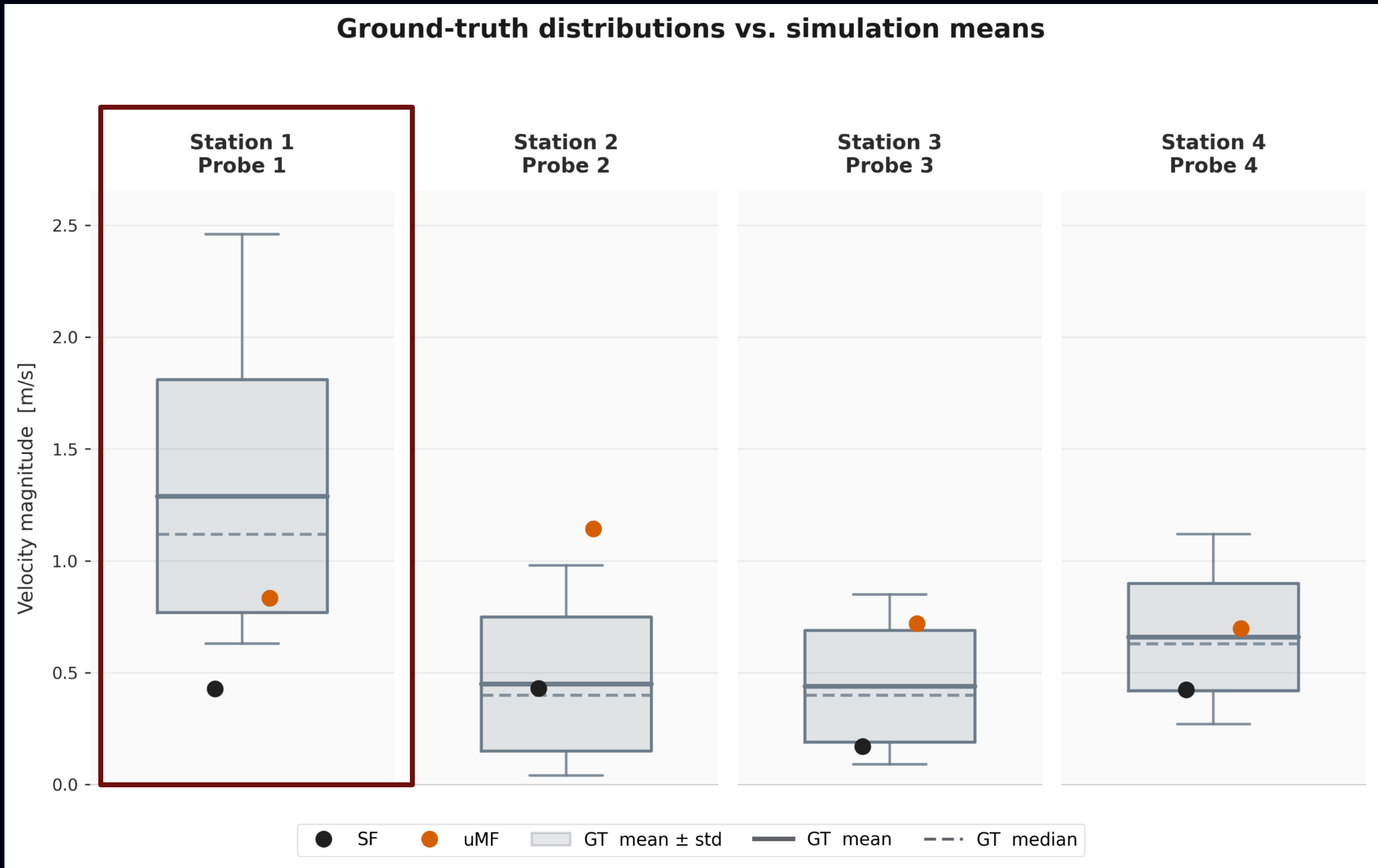
Distributions of the 5-minute measurements for the simulated hour (minimum, maximum, mean, median, standard deviation). Simulation predictions are overlaid as markers.

WIND-SPEED PREDICTION COMPARISON



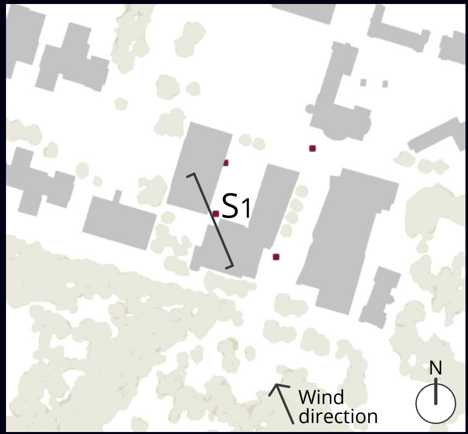
SF tends to under-predict wind speed, while uMF tends to over-predict (height 1.8m)

STATION 1



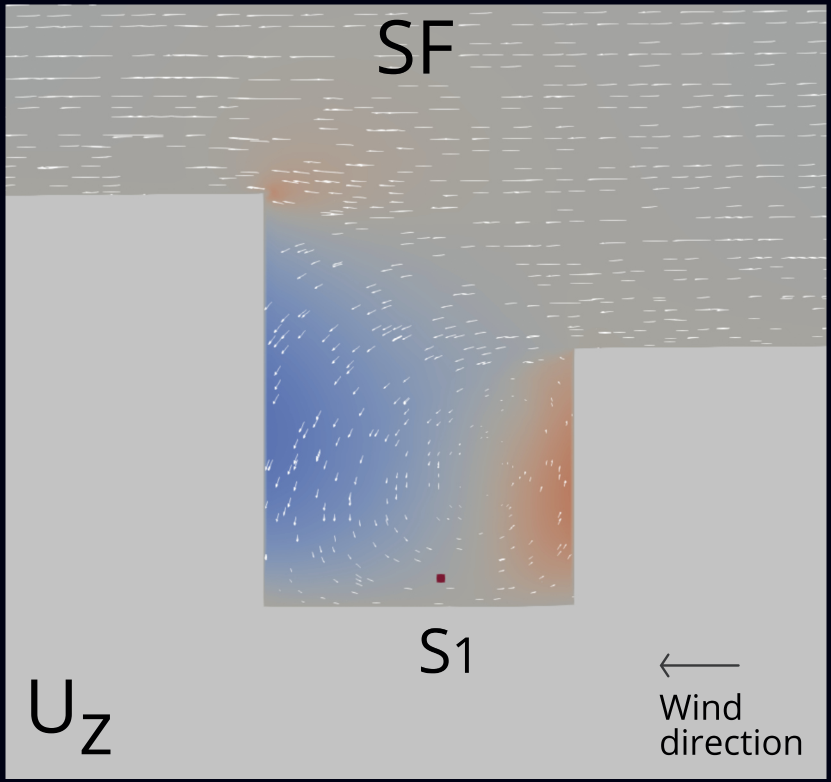
Ground-truth distributions vs. simulation means
Station 1
Probe 1
Station 2
Probe 2
Station 3
Probe 3
Station 4
Probe 4
Velocity magnitude [m/s]
2.5
2.0
1.5
1.0
0.5
0.0
SF
uMF
GT mean ± std
GT mean
GT median

STATION 1

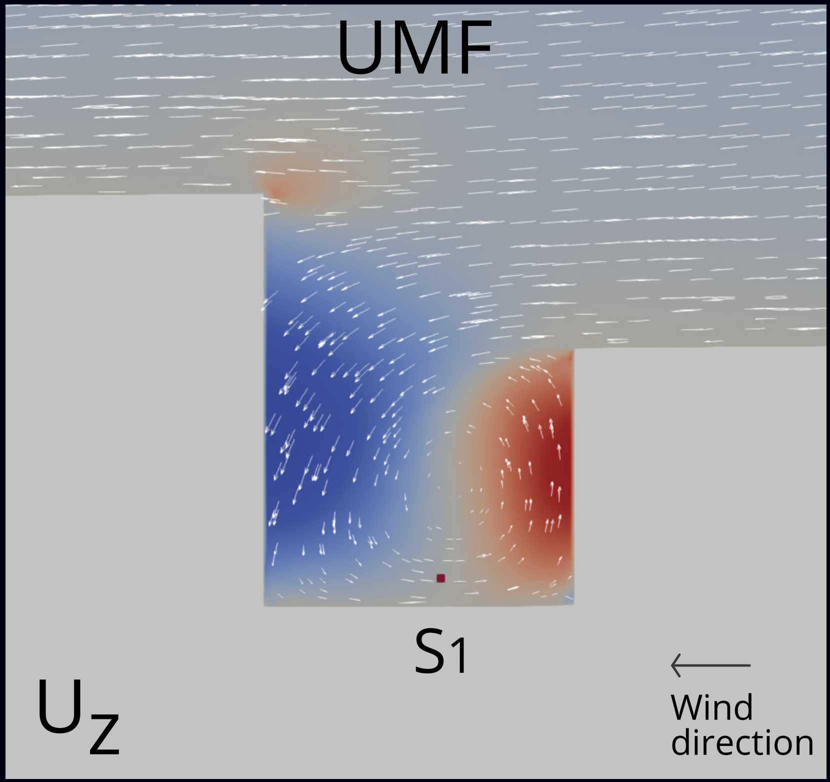


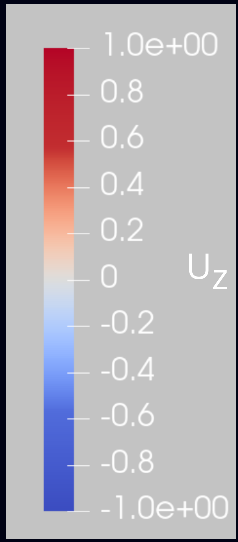
Strong vertical motion is evidence of buoyancy contributing non-negligibly to the flow at this location

Vertical velocity component Uz



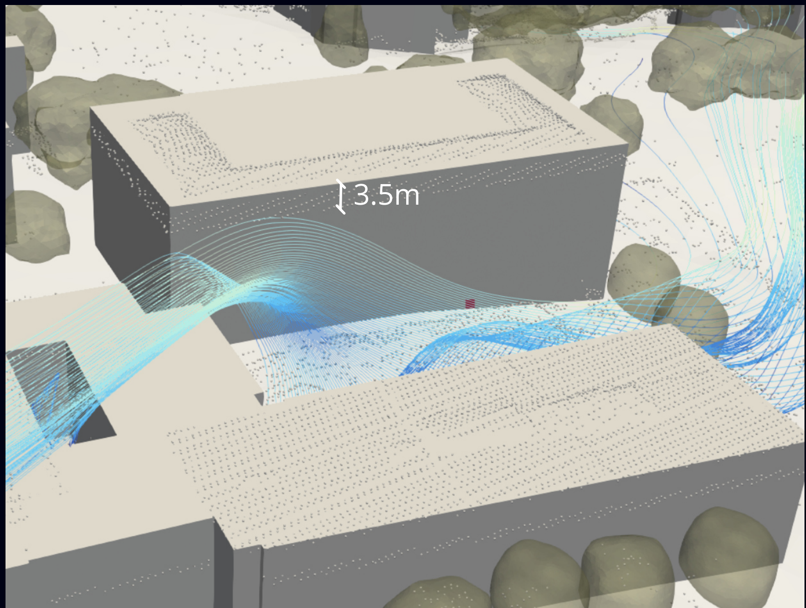
Vertical velocity component Uz





WIND-SPEED PREDICTION COMPARISON

Discrepancies can be explained by geometric simplification, among other simplifications



LIMITATIONS

Single one-hour window under one inflow direction

Anemometer accuracy (±0.89 m/s) and range starting at 0.89m/s

Simplified building reconstruction LoD 1.2

Simplified Vegetation representation (e.g. missing evapotranspiration)

Simplified Material and Solid thickness

RECOMMENDATIONS

Single one-hour window under one inflow direction

Simulate longer time windows

Anemometer accuracy (±0.89 m/s) and range starting at 0.89m/s

Simulate time windows with higher wind forcing

Simplified building reconstruction LoD 1.2

Development of robust preparation utilities for realistic geometry

Simplified Vegetation representation (e.g. missing evapotranspiration)

Use VEG module

Simplified Material and Solid thickness

CONCLUSION: WHEN IS UMF WITH COMPLEX GEOMETRY WORTH THE COST?

Is the regime one in which buoyancy matters?
Can the analyst absorb the case-setup overhead?

However...
a robust conclusion would **require mittigating the limitations of this study**

THANK YOU, QUESTIONS?

MODEL SETUP DECISIONS

2

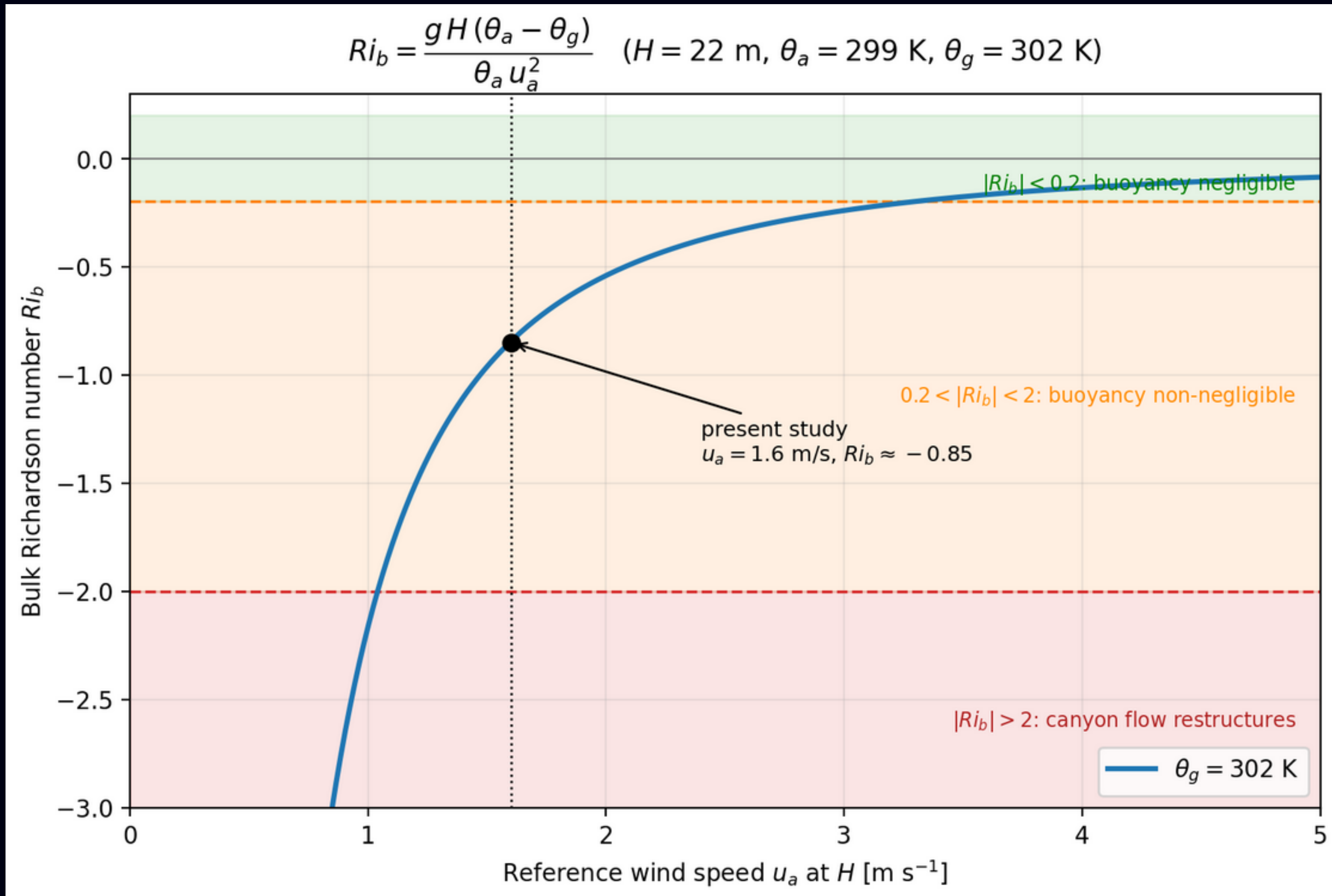
SF and uMF setup and execution

RAD - Radiation
Short-wave qs = solarLoadRadiationViewFactor (Ray-cast diffuse and reflected radiation weighted by the surface albedo)

Albedo is a measure of the amount of sunlight that a surface reflects. It is calculated as a ratio between 0 (total absorption) and 1 (total reflection).

long-wave flux qr = greyDiffusiveRadiationViewFactor (each surface emits and absorbs long-wave radiation as a gray, diffuse body with a prescribed emissivity)
Emissivity how well an object is able to **emit energy as thermal radiation** compared to a perfect emitter (blackbody).

MODEL SETUP



$Ri_b = \frac{g H (\theta_a - \theta_g)}{\theta_a u_a^2}$ ($H = 22$ m, $\theta_a = 299$ K, $\theta_g = 302$ K)
Bulk Richardson number Ri_b
Reference wind speed u_a at H [m s^{-1}]
$|Ri_b| < 0.2$: buoyancy negligible
$0.2 < |Ri_b| < 2$: buoyancy non-negligible
$|Ri_b| > 2$: canyon flow restructures
present study
$u_a = 1.6$ m/s, $Ri_b \approx -0.85$
$\theta_g = 302$ K
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
0
1
2
3
4
5

GRID INDEPENDENCE TEST

Mesh	Cell count N	Δh_r (m)	Refinement ratio
Fine	35 524 066	3.18	–
Nominal	16 214 605	4.13	1.30
Coarse	7 859 572	5.26	1.30

Convergence parameter	U	p	k	ε
Apparent order of convergence (median)	3.6	3.9	4.2	4.4
Relative error (%, median)	0.9	1.7	1.7	3.5
Extrapolation error (%, median)	0.7	0.9	0.9	1.7
GCI (%, median)	0.9	1.2	1.2	2.1

Result: solutions don't change significantly if a finer mesh is used

Apparent order of convergence: how fast the error shrinks as the mesh refines

Relative error: direct difference between the fine and nominal solutions.

Extrapolated error: distance from the Richardson-extrapolated "zero-cell-size" estimate.

GCI: percentage uncertainty band on the nominal solution attributable to mesh resolution.

LIMITATIONS

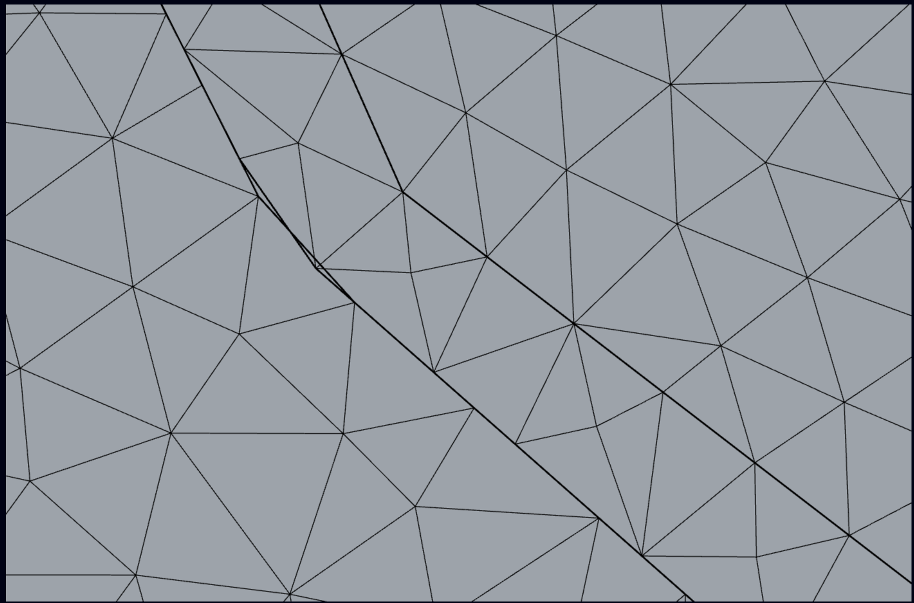
Anemometer accuracy (±0.89 m/s) and range starting at 0.89m/s

Single one-hour window under one inflow direction

- **Below that wind speed, the sensor reads an unreliably low value.**
- Intrinsic **limitation of this type of study** because of **calm winds** happening most of the time.

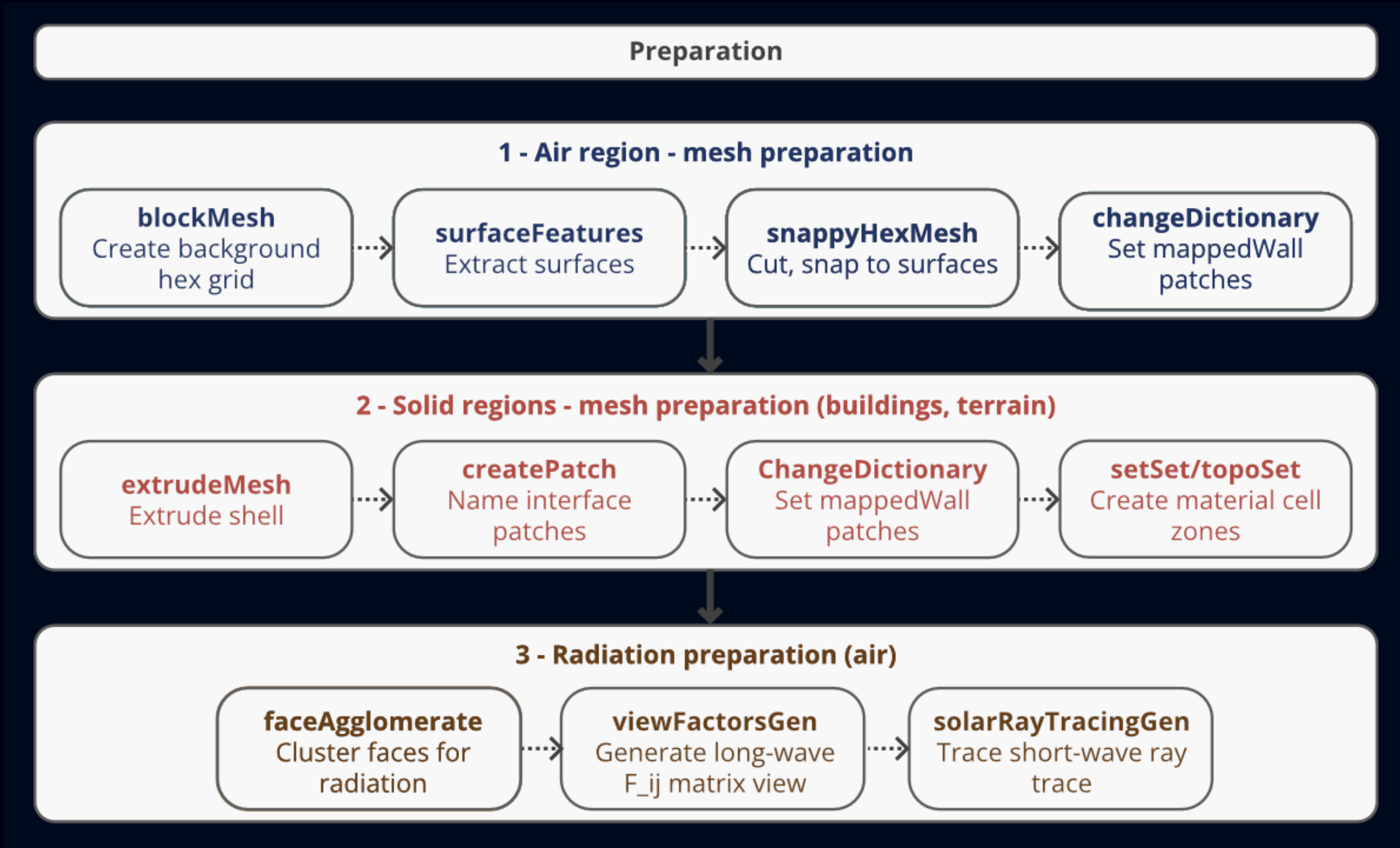
- Simulation of **many more time windows** would help to **minimize** this
- Include windows with **stronger wind forcing** above the Anemometer’s accuracy range, but **limit the study to only a few hour windows**

FEASIBILITY OF APPLICATION

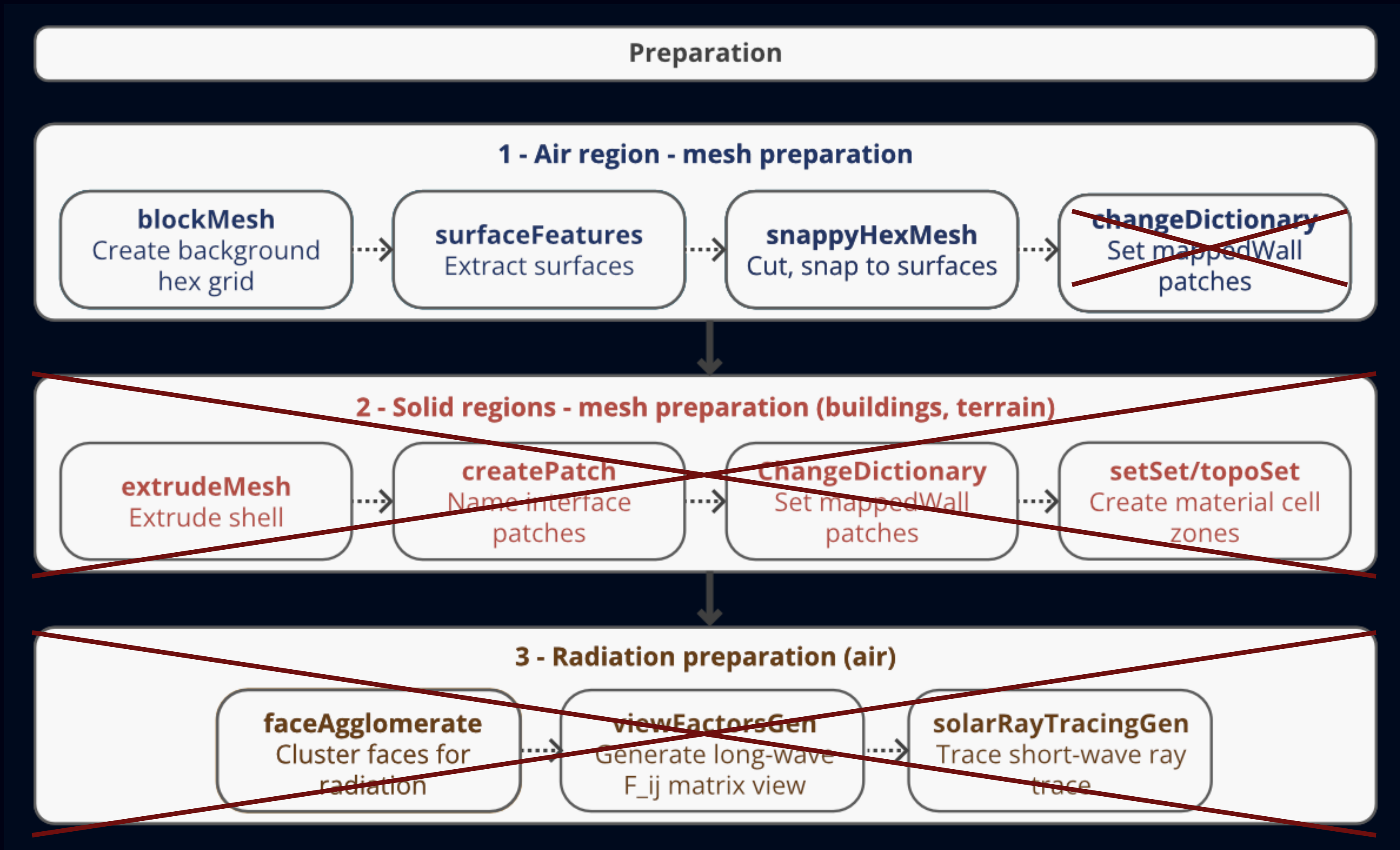


Isotropic re-meshing altering surface edges

URBAN MICROCLIMATE FOAM



SIMPLE FOAM


Preparation
1 - Air region - mesh preparation
blockMesh
Create background hex grid
surfaceFeatures
Extract surfaces
snappyHexMesh
Cut, snap to surfaces
changeDictionary
Set mappedWall patches
2 - Solid regions - mesh preparation (buildings, terrain)
extrudeMesh
Extrude shell
createPatch
Name interface patches
ChangeDictionary
Set mappedWall patches
setSet/topoSet
Create material cell zones
3 - Radiation preparation (air)
faceAgglomerate
Cluster faces for radiation
viewFactorsGen
Generate long-wave F_ij matrix view
solarRayTracingGen
Trace short-wave ray trace

DISCUSSION 2: WHY UMF OVER-PREDICTS ON AVERAGE?

Hypothesis:

The CMU campus borders Schenley Park to the southeast and sits in a well-vegetated residential surrounding; the **omitted vegetation cooling and humidity flux is probably significant.**

RECOMMENDATIONS

Simplified building reconstruction LoD 1.2

Simplified Material and Solid thickness

Robust preparation utilities for **realistic geometry**

- more robust **faceAgglomerate**
- building-**footprint simplification**
- **terrain-mesh refinement**,
- more **robust refinement of building** meshes
- diagnostic tools that **flag problematic faces** before a run.

Geometric-reconstruction

- Automated pipelines with utilities tailored to uMF

RECOMMENDATIONS

Single one-hour window under one inflow direction

Anemometer accuracy (±0.89 m/s) and range starting at 0.89m/s

Validation and Methodology

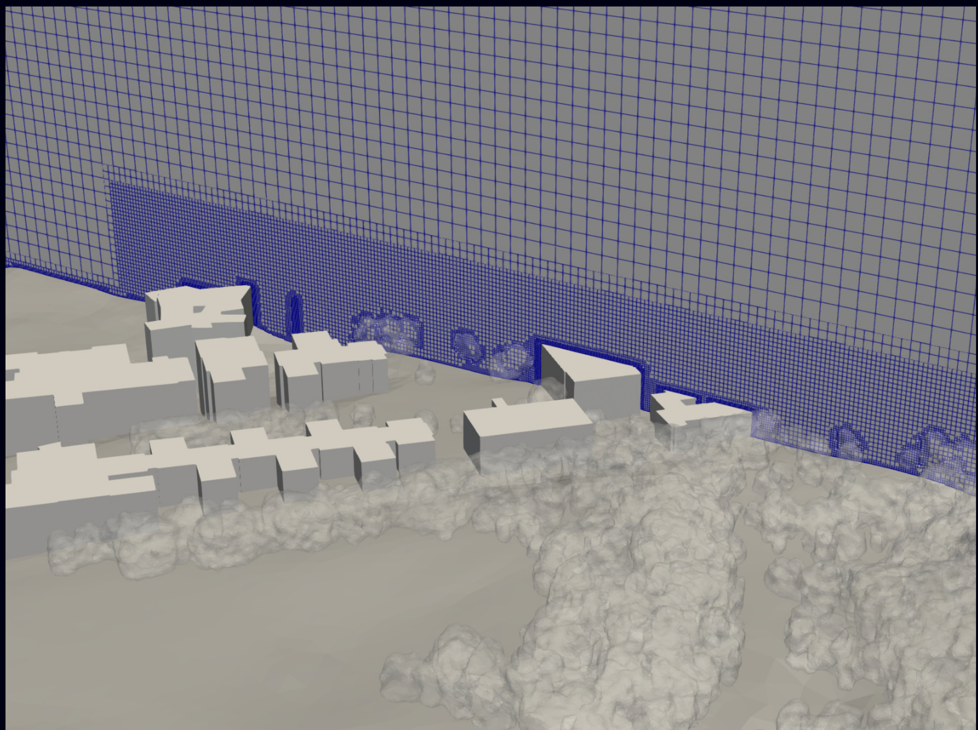
- Extend the validation to **longer time windows**
- Include windows with **stronger wind forcing** above the Anemometer's accuracy range
- **Various inflow** directions
- **Incorporate** uMF VEG module

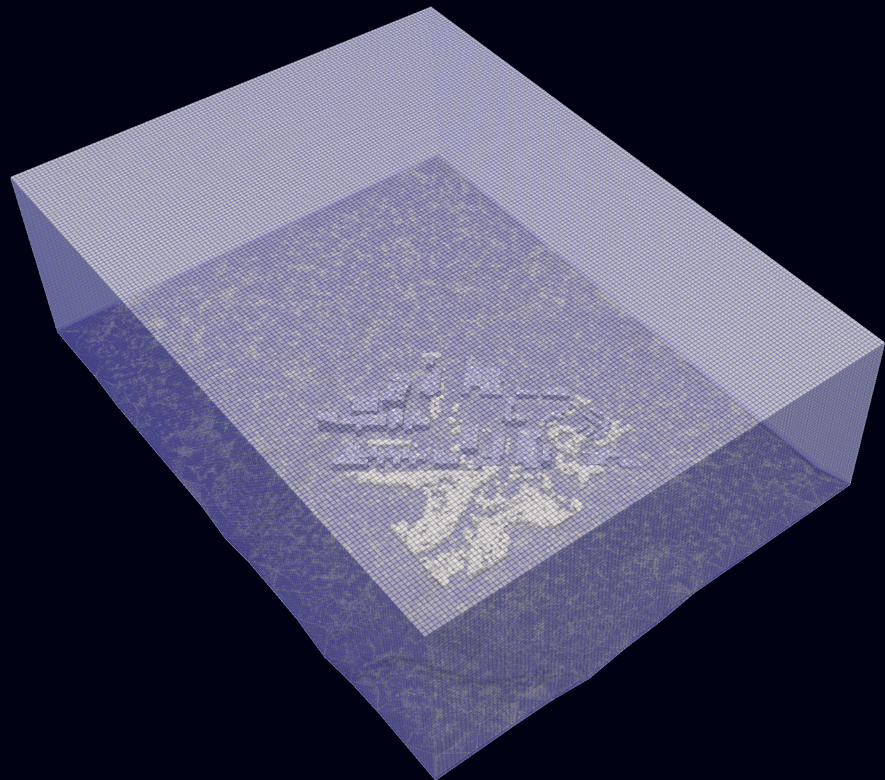
Solver

- Boundary-condition formulations adaptable to circular domains .

URBAN MICROCLIMATE CFD

Model of the air and solids





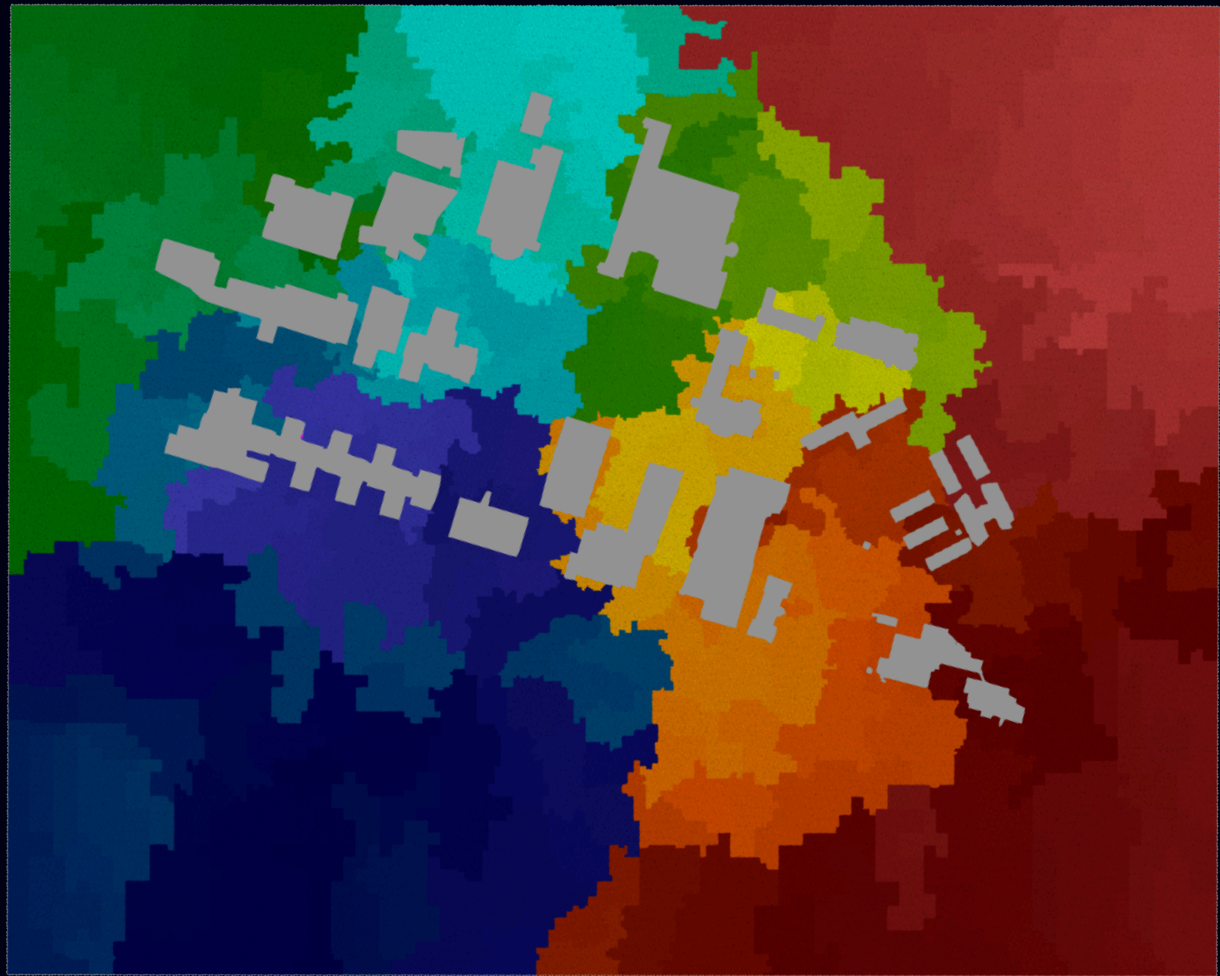
RADIATION PREPARATION

1.3

3 - Radiation preparation (air)

faceAgglomerate

Grouping faces is fundamental to make the calculation of rays more efficient in a complex geometry



MODEL SETUP ASSUMPTIONS

2

SF and uMF setup and execution

simpleFOAM	**urbanMicroclimateFoam**
AIR (CDF)	Coupled (AIR HAM RAD)
Neutral; temperature neglected	Solve Air temperature & humidity (299K, 0.014 kg/kg Mesonet ASOS)

Vegetation as porosity zone

Turbulence Realisable k-epsilon

Roughness z0 = 0.5 m

ATM boundary layer inlet profiles

Second order schemes

$$U(z) = \frac{u^*}{\kappa} \ln\left(\frac{z+z_0}{z_0}\right)$$

$$k(z) = \frac{u^{*2}}{\sqrt{C_\mu}}$$

$$\epsilon(z) = \frac{u^{*3}}{\kappa\,(z+z_0)}$$

MODEL SETUP ASSUMPTIONS

2

SF and uMF setup and execution

urbanMicroclimateFoam

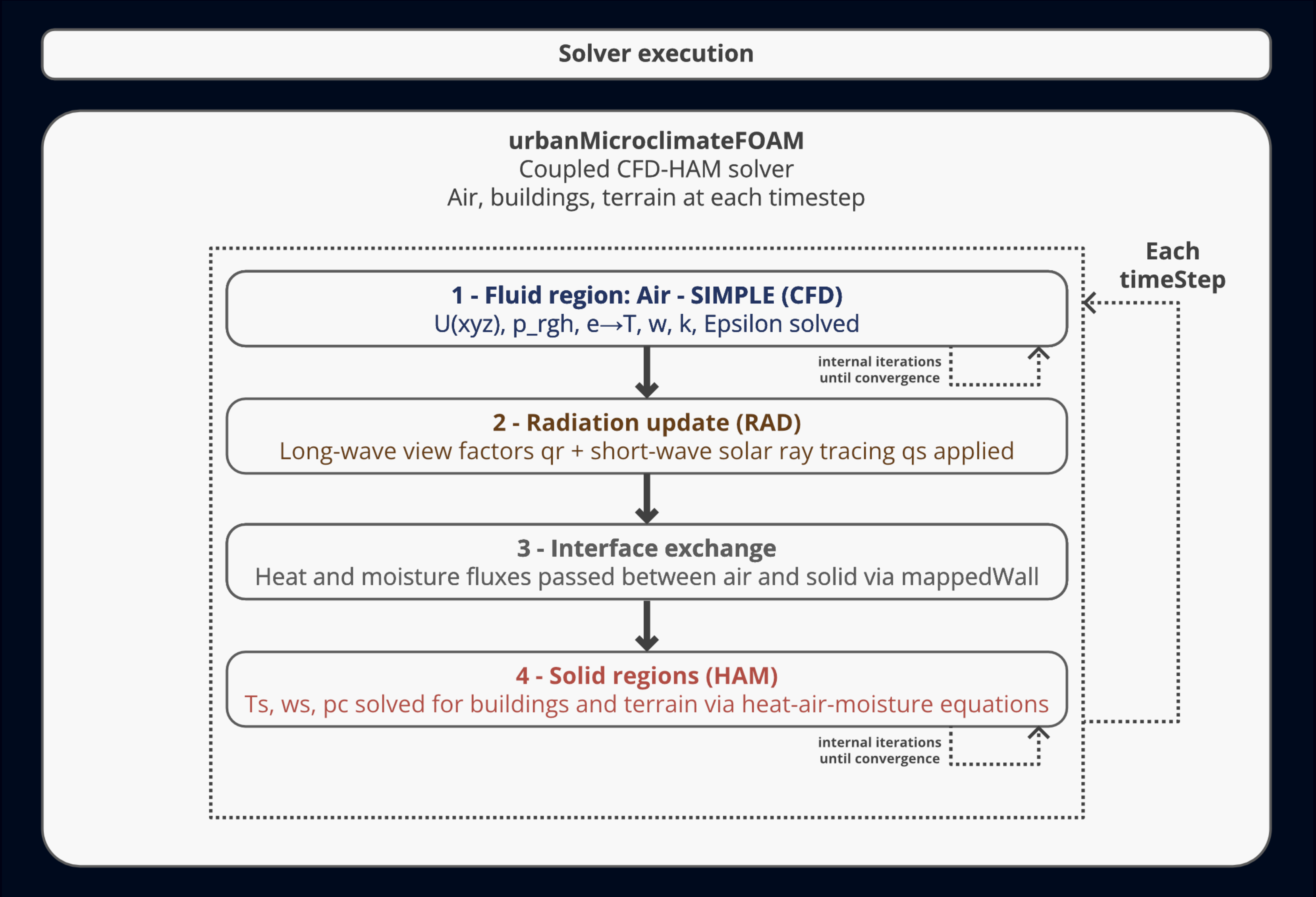
Surface T (Brick 305K, Asphalt 302K) (MORICHI)

Buildings + Terrain 0.1m width, Tutorial materials

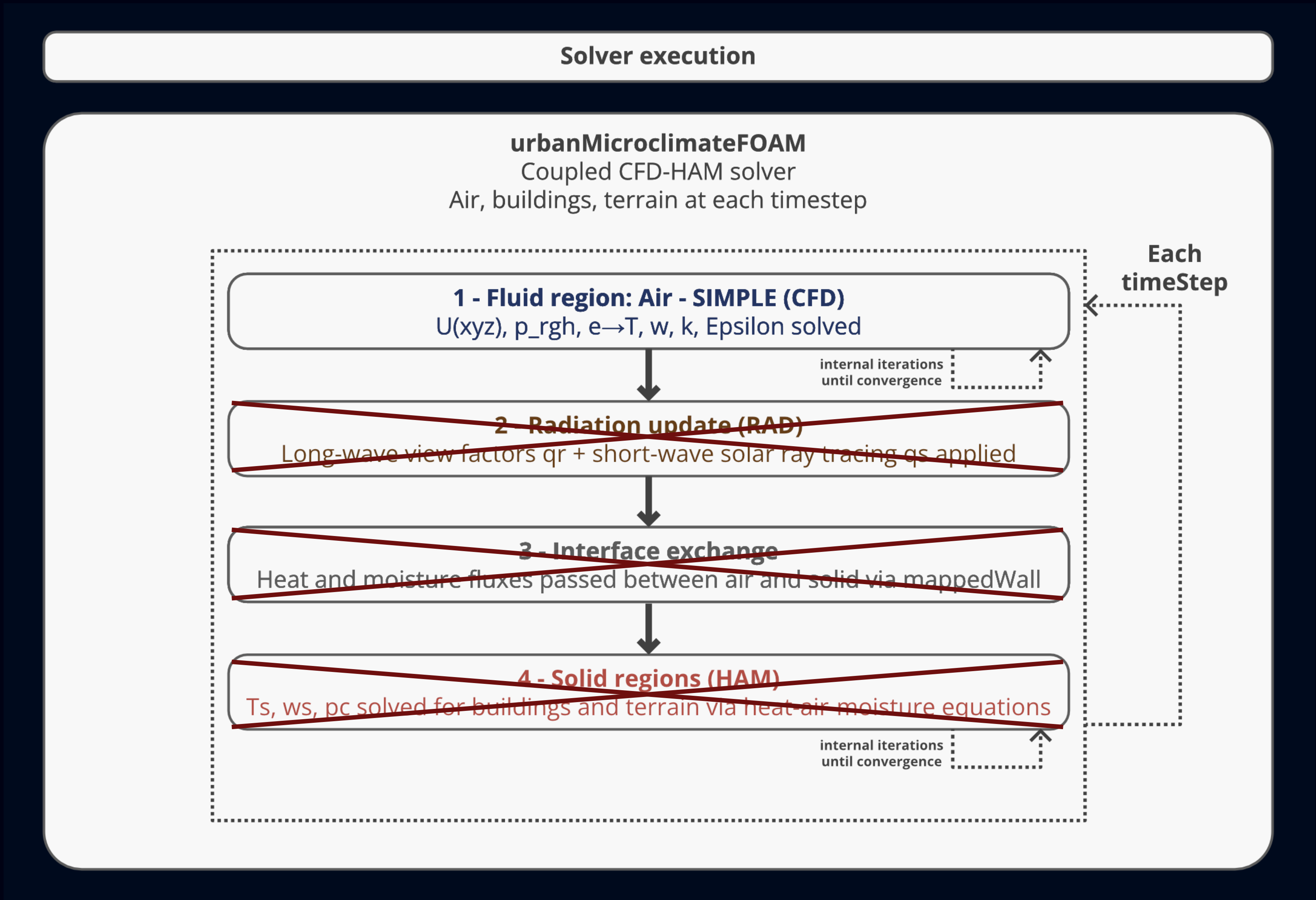
Shortwave solarLoadRadiationViewFactor (direct + diffuse + re9ected), open sky

Longwave greyDiffusiveRadiationViewFactor (grey, diffuse), Emissivity 0.9, Albedo 0.4

URBAN MICROCLIMATE FOAM



SIMPLE FOAM


Solver execution
urbanMicroclimateFOAM
Coupled CFD-HAM solver
Air, buildings, terrain at each timestep
Each timeStep
1 - Fluid region: Air - SIMPLE (CFD)
U(xyz), p_rgh, e→T, w, k, Epsilon solved
internal iterations until convergence
2 - Radiation update (RAD)
Long-wave view factors qr + short-wave solar ray tracing qs applied
3 - Interface exchange
Heat and moisture fluxes passed between air and solid via mappedWall
4 - Solid regions (HAM)
Ts, ws, pc solved for buildings and terrain via heat-air-moisture equations
internal iterations until convergence

WIND-SPEED PREDICTION COMPARISON

Station 1 provides the most robust answer when looking at a single station

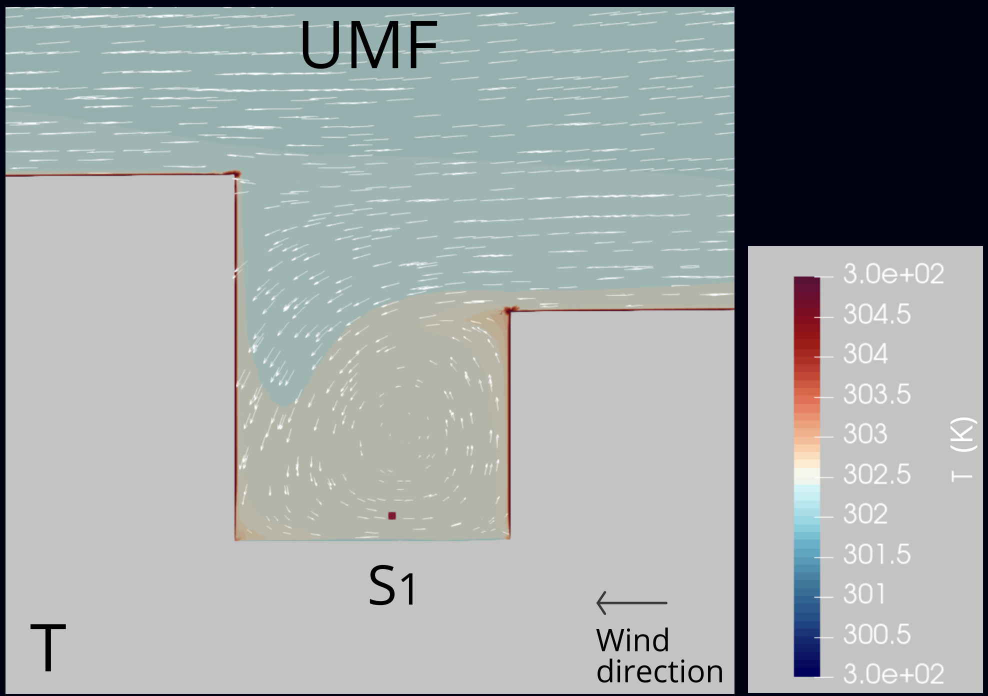
- **above anemometer accuracy range, that starts at 0.89 m/s**
- **29 percentage point reduction in relative error**.

The remaining stations are consistent with this picture but cannot be drawn independently of instrument uncertainty

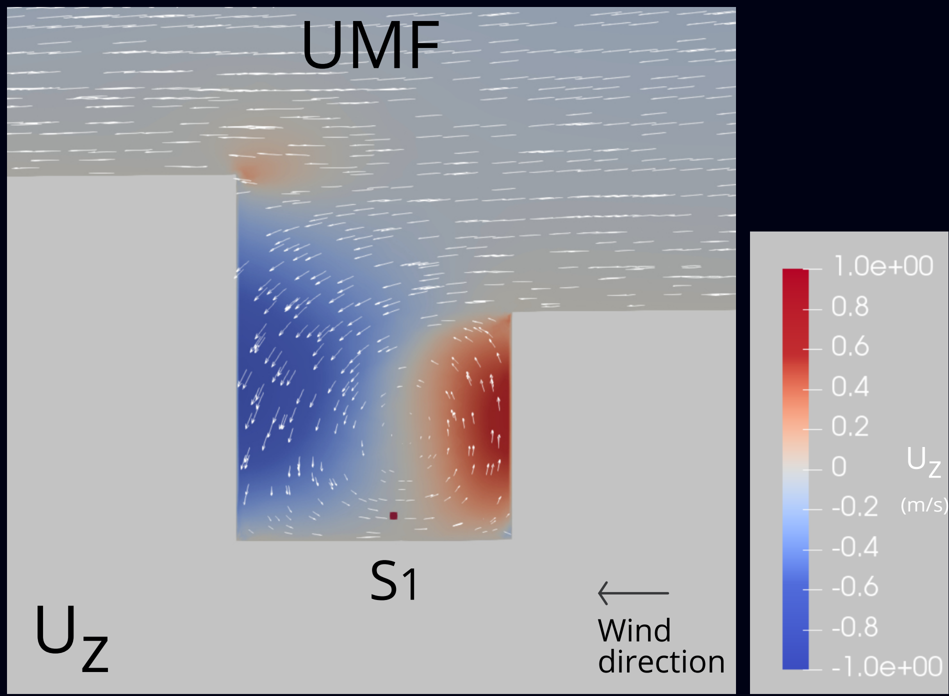
Station	U_o [m/s]	σ_o [m/s]	U_{SF} [m/s]	$\varepsilon_{rel,SF}$ [%]	U_{uMF} [m/s]	$\varepsilon_{rel,uMF}$ [%]	Difference (SF→uMF)
Station 1	1.29	0.52	0.43	67	0.80	38	−29 pp
Station 2	0.45	0.30	0.43	4	1.07	139	+135 pp
Station 3	0.44	0.25	0.17	61	0.64	46	−15 pp
Station 4	0.66	0.24	0.42	36	0.66	1	−35 pp

STATION 1

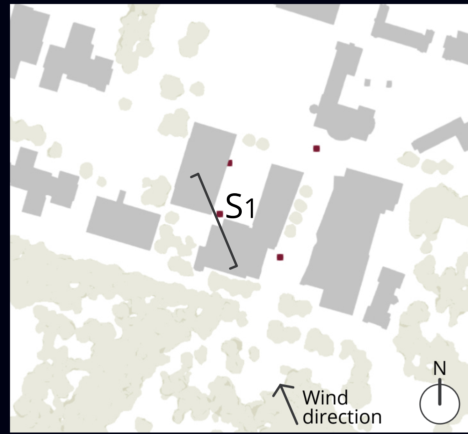
Temperature



Vertical velocity component Uz

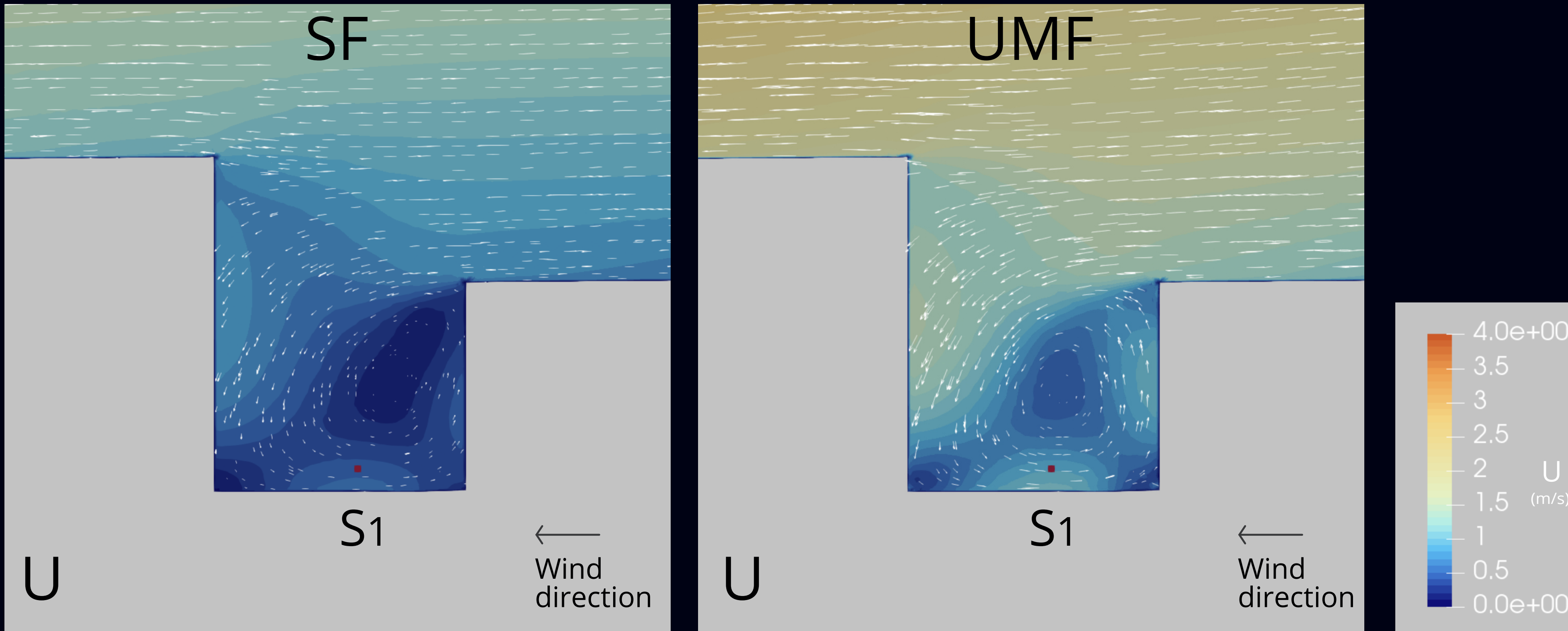


STATION 1

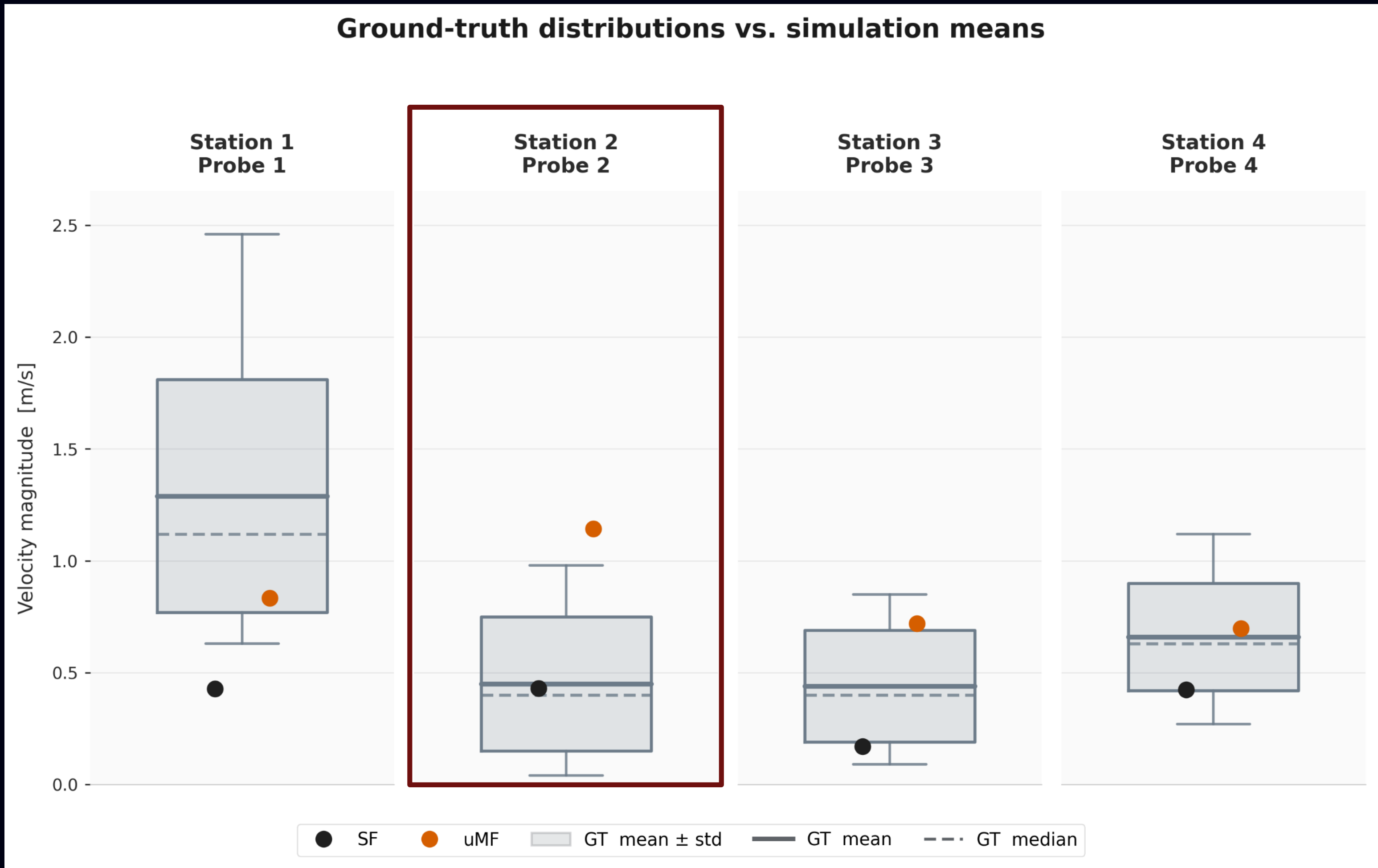


Velocity U

Velocity U

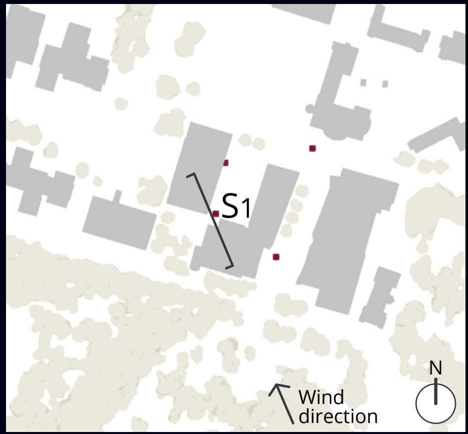


STATION 2

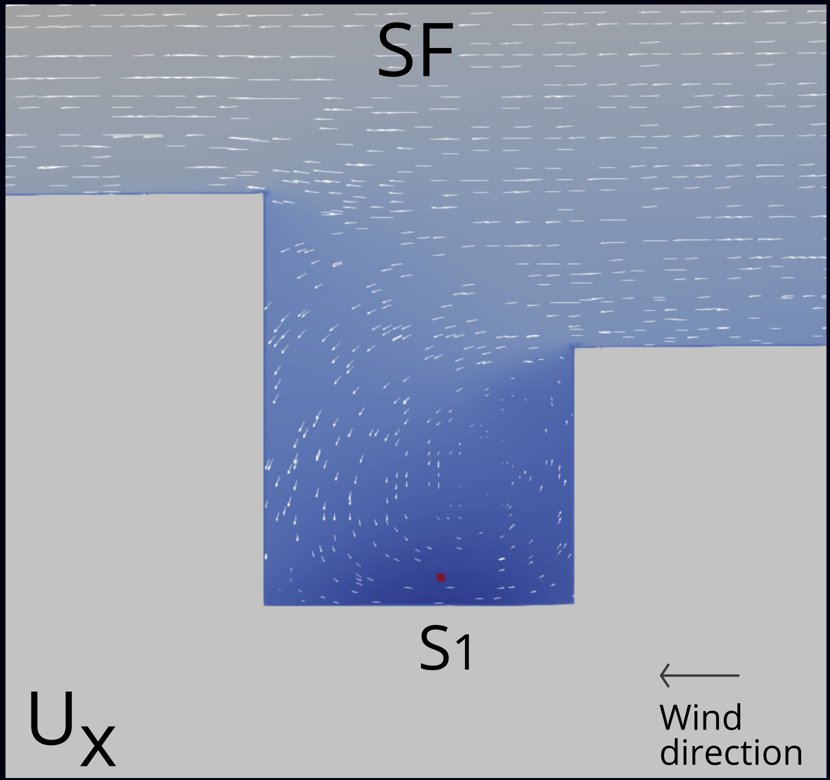


Ground-truth distributions vs. simulation means
Station 1
Probe 1
Station 2
Probe 2
Station 3
Probe 3
Station 4
Probe 4
Velocity magnitude [m/s]
2.5
2.0
1.5
1.0
0.5
0.0
SF
uMF
GT mean ± std
GT mean
GT median

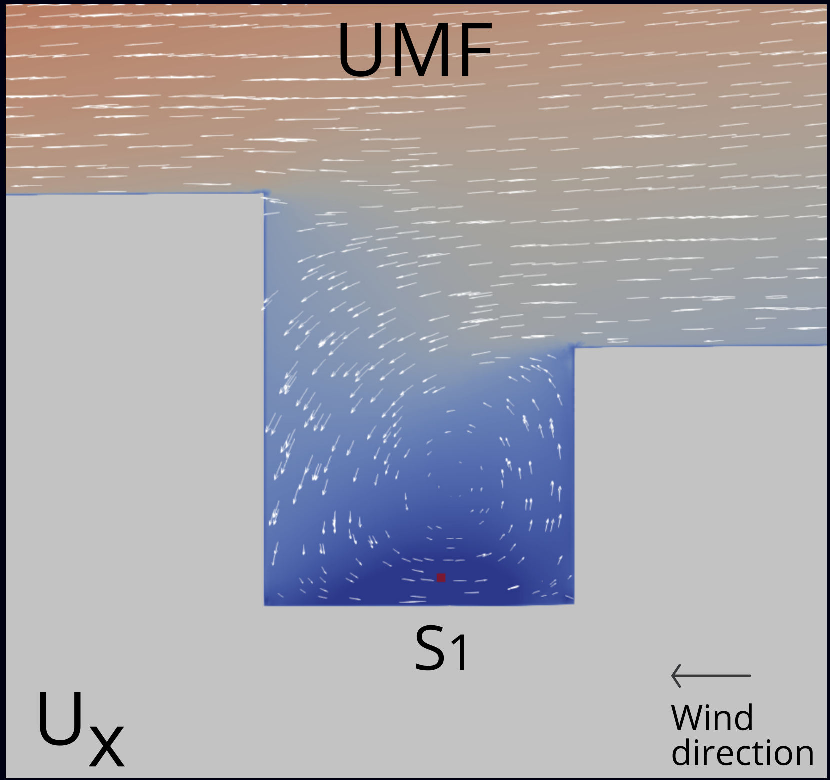
STATION 1

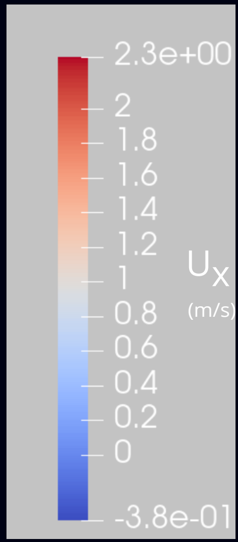


Horizontal velocity component Ux



Horizontal velocity component Ux





WIND-SPEED PREDICTION COMPARISON

The indicators evidence these tendencies

Metric	Acceptance	SF Value	SF Pass	uMF Value	uMF Pass	Reduction (SF→uMF)
FB	$\lvert FB \rvert < 0.3$	+0.65	No	−0.11	Yes	−83%
NMSE	NMSE < 4	0.85	Yes	0.30	Yes	−65%
MG	MG < 1	1.89	No	0.83	Yes	−80%
VG	VG < 1.5	1.79	No	1.32	Yes	−59%

Sabatino et al. (2011)
Chang and Hanna (2004)

Average improvement SF to uMF of 71%.

$$FB = \frac{\overline{C_o} - \overline{C_p}}{0.5(\overline{C_o} + \overline{C_p})},$$ Fractional bias

$$NMSE = \frac{\overline{(C_o - C_p)^2}}{\overline{C_o}\,\overline{C_p}},$$ Normalised mean square error

$$MG = \exp(\overline{\ln C_o} - \overline{\ln C_p}),$$ Geometric mean bias

$$VG = \exp(\overline{(\ln C_o - \ln C_p)^2}),$$ Geometric variance

$$FAC2 = \text{fraction of data that satisfy } 0.5 \leq \frac{C_p}{C_o} \leq 2.0,$$

$$\varepsilon_{rel} = \frac{|C_p - C_o|}{C_o}.$$

where:

C_p: model predictions;

C_o: observations;

$\overline{C}$: average over the dataset;

ε_{rel}: relative error at each station reported as a percentage.