EPFL

CIVIL-309: URBAN THERMODYNAMICS

Dr. Jaafar Younes

Lecture 05:

Urban modeling and computational tools

31 October 2025

Course Schedule

7	24.10		BREAK	
8	31.10	1 x 45’	**Urban modeling and computational tools**	JY
		1 x 45’	Introduction to the web tool **CityTherm** (part II)	JY
		1 x 45’	**Introduction to the course project II**	JY
9	07.11	2 x 45’	**Building-environment interaction:** thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45’	**Supervised group work - course project II**	JY
10	14.11	2 x 45’	**Ground-environment interaction:** ground properties, thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45’	**Supervised group work - course project II**	JY
11	21.11	2 x 45’	**Water body - environment interaction**: thermal, aerodynamic, and hydrodynamic interaction	DK
		1 x 45’	**Supervised group work - course project II**	JY
12	28.11	2 x 45’	**Vegetation – environment interaction:** characteristics of vegetation, evapotranspiration, aero- and thermal interaction	DK
		1 x 45’	**Supervised group work - course project II**	JY
13	05.12	2 x 45’	**Human Outdoor Comfort:** Parameters affecting human comfort and comfort indices (UTCI, PET)	JY
		1 x 45’	**Supervised group work - course project II**	JY
14	12.12	1 x 45’	**Climate-Sensitive Urban Design**: complex interaction of all urban elements and their effect on UHI and outdoor comfort	DK
		2 x 45’	**Supervised group work - course project II**	JY
15	19.12	3 x 45’	Supervised group work on the course project II **Course project II submission deadline: 16:00 on December 19**	DK, JY

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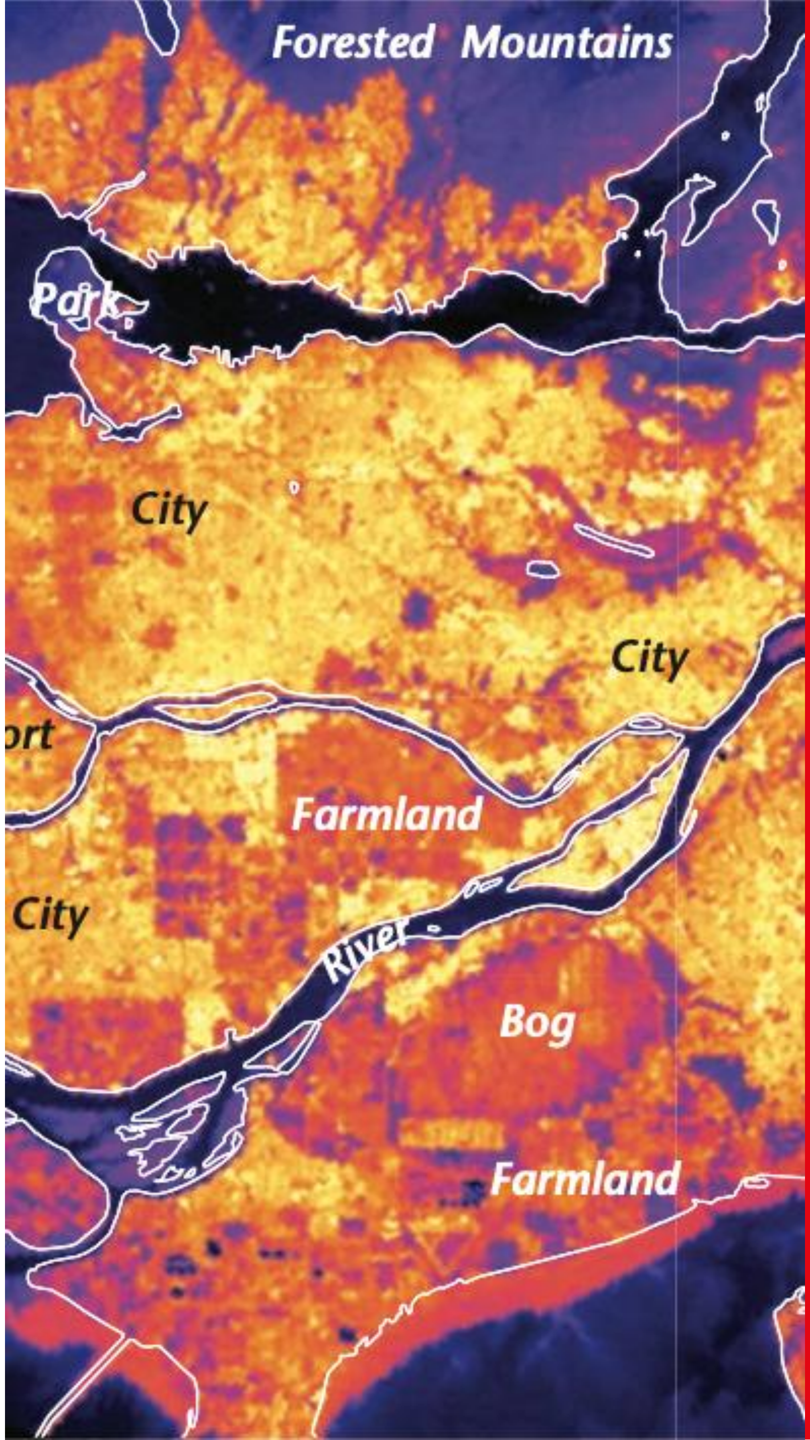


CONTENT:

I. The "Why" and "How" of Urban Modeling

- **Objectives: Why do we model the urban environment?**
- **Physical vs. Numerical Modeling**

II. Physical Modeling

- **Examples: Wind Tunnels and Water Tunnels**
- **The Critical Challenge: Similarity Requirements**

III. Numerical Modeling

- **Understanding the Scales of Numerical Models: Mesoscale (City-wide), Microscale (Neighborhood/Street)**

IV. A Taxonomy of Computational Tools

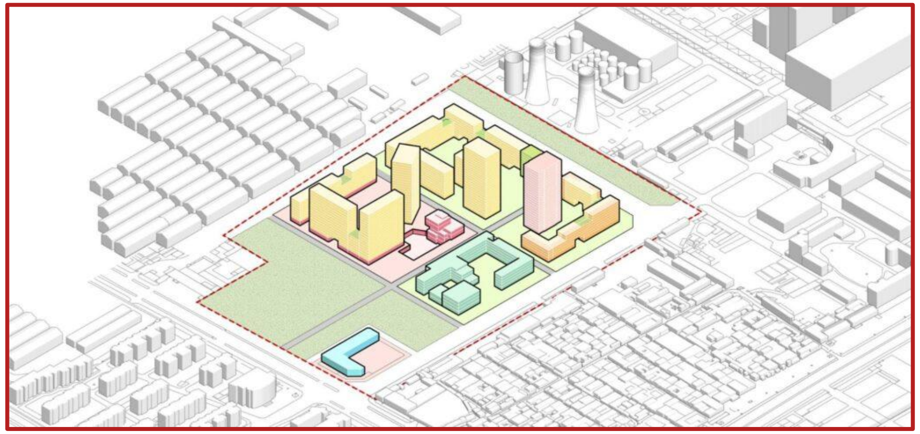
- **Mesoscale:** WRF, Meso-NH, ACCESS**; Microscale (CFD):** ANSYS Fluent, OpenFOAM**; Microscale (Specialized):** ENVI-met, Palm**; District & Energy Scale:** CitySIM, City Energy Analyst (CEA), UMEP

V. Synthesis & Key Takeaways

- **Model Integration and Conclusions**

Introduction: Why to Model the Urban Environment?

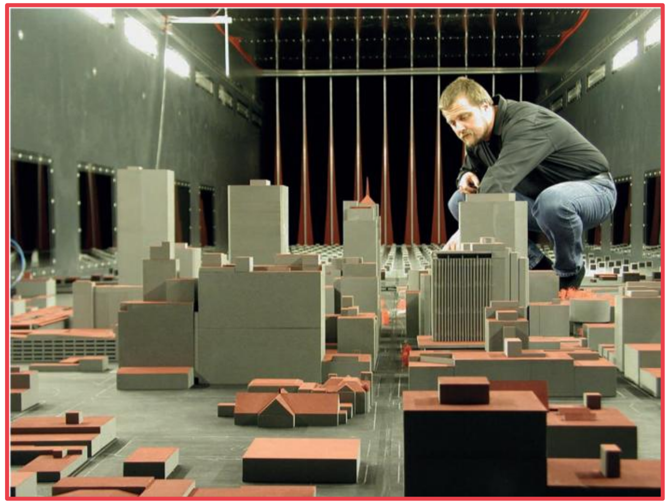
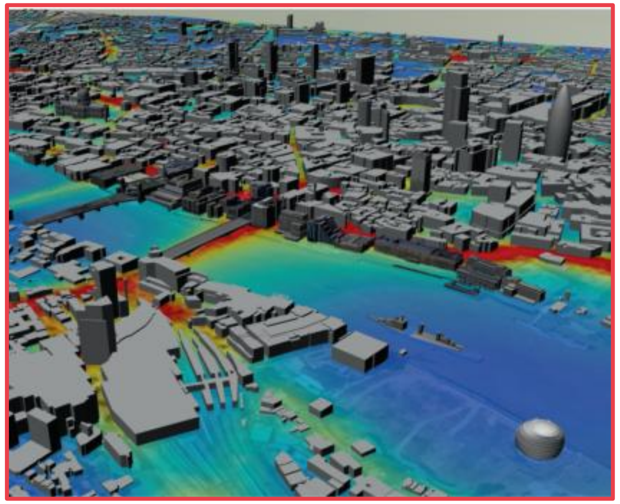
- A **model** is a simplification of a complex reality (the city) used to understand, predict, and test "what-if" scenarios.



- Core **Objectives in Urban Thermodynamics**:
  - **Predict:** Urban Heat Island (UHI) intensity, microclimate variations, building energy consumption.
  - **Assess:** Pedestrian thermal comfort, air pollutant dispersion, wind safety.
  - **Optimize:** Benefits of mitigation strategies (e.g., green roofs, cool pavements, urban form).

- **Two Fundamental Approaches:** We can either build a small-scale version of the city (**Physical**) or build a mathematical representation (**Numerical**).

Urban modelling: Physical vs. Numerical Modeling

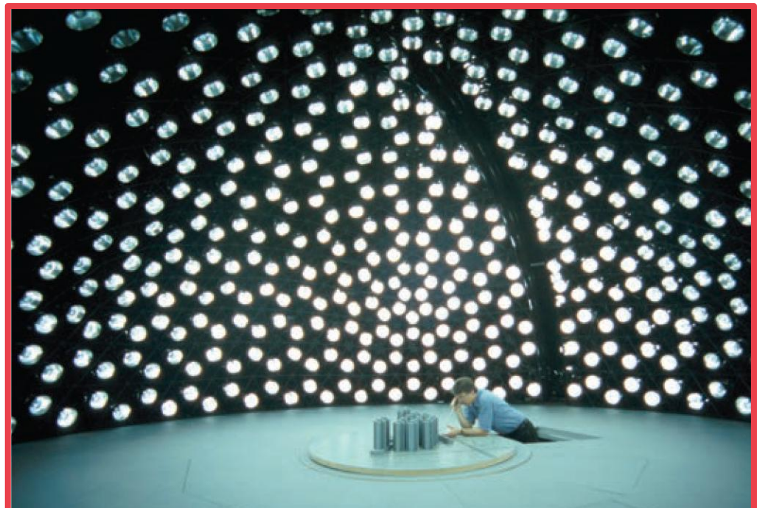
Feature	Physical Modeling	Numerical Modeling
Method	Scaled-down physical replica of the urban area.	Mathematical representation using governing equations.
Examples	- **Wind Tunnels:** Air is blown over a model - **Water Tunnels:** Water is used as the fluid.	- **Microscale Models (i.e. CFD):** Solves fluid flow equations. - **Mesoscale Models:** Solves atmospheric equations.
Pros	- "Real" physics; Provides experimental control - Excellent for validating numerical models. - Can capture detailed, highly complex, unknown turbulence phenomena.	- High flexibility (easy to change geometry, boundary conditions). - Provides data at every point in the domain (velocity, T, P). - Cost-effective (computationally). - Can isolate specific physical effects.
Cons	- Expensive and time-consuming to build; Requires access to specialized facilities (flume, wind tunnel). - Inflexible (a new model must be built for each design change); Requires careful design **- Difficulty in meeting similarity requirements.**	- Results depend heavily on setup. "Garbage In, Garbage Out." - Requires validation against physical data and field observations - Assumptions can be restrictive - Computationally intensive (can require supercomputers). - Relies on simplified models (e.g., for turbulence, radiation).
Demon-stration	 Downtown area of a city (Oklahoma City,United States). Oke, Urban Climates.	 Numerical Model of a city

Urban modelling: Physical modelling

A **physical model** is a surrogate of a real-world system that is simplified and usually scaled.

- It can be built:
  - Indoors with *controlled* conditions (Laboratory Models)
  - Outdoors under *real* meteorological conditions

- Both Laboratory models and Outdoor models are usually used for studying: Radiation, Airflow, Temperature

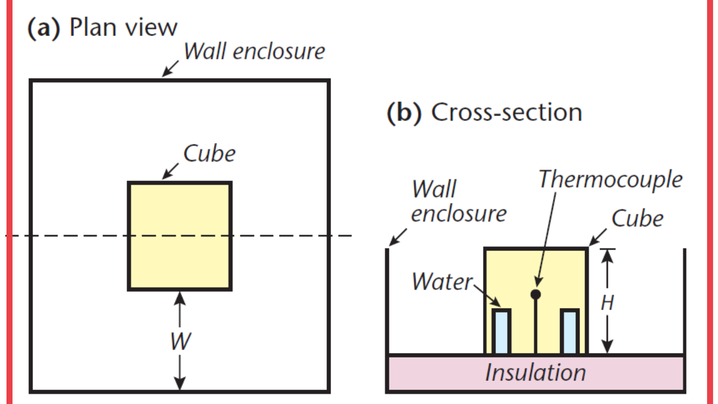


Welsh School of Architecture, Cardiff University

Example of Laboratory Model of Radiation Exchange: Heliodon (Sun machine)

Source: Oke, Urban Climates

Example of Outdoor Model used for studying effect of urban structure on airflow, turbulence, dispersion, radiation

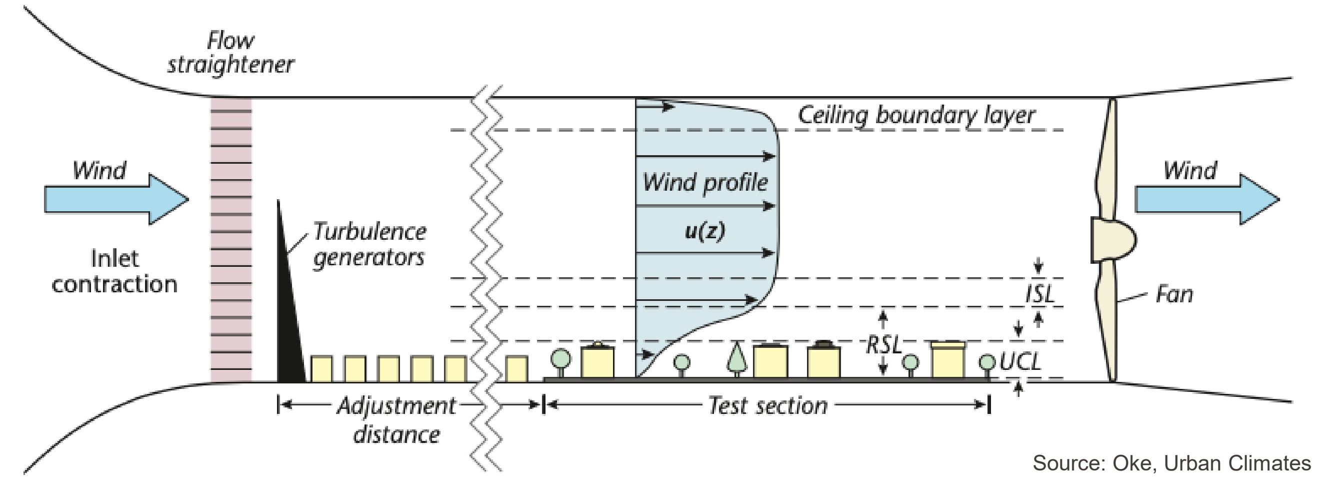


Source: Mills 1997b

A building, surrounded by a wall enclosure, representing the neighboring buildings

Urban modelling: Scaling and Similitude

- A **wind tunnel, water flume** or **water tank** can be used to model the urban airflow



Source: Oke, Urban Climates

- Physical modelling require similarity (or **similitude**) with the real system it seeks to mimic.

- Similitude is achieved by ensuring a consistent match between **critical ratios** of properties in both the scale model and the prototype. This is informed by a **dimensional analysis**

- it is often enough to achieve similarity in one or more key aspects: **Geometric Similarity, Dynamic Similarity** (*e.g. Re =* $\frac{\rho U L}{\mu}$*: ratio of inertial forces to viscous forces*), and **Thermal Similarity.**

About the wind tunnel at EPFL:
https://www.epfl.ch/labs/wire/facilities/wind-tunnel/

Urban modelling: Numerical Modeling, Scales

- **Numerical models** simulate real-world phenomena using a **set of equations.**

- No single numerical model can capture everything from regional weather down to the flow around a single person. We must choose **the right tool for the right scale**.

Mesoscale (Kilometers to Hundreds of km):
- **Focus:** City-scale phenomena. How the entire urban area interacts with regional weather.
- **Physics:** Solves atmospheric dynamics. The city itself is often simplified or "parameterized" as a rough, warm surface (using an Urban Canopy Model, or UCM).
- **Used for:** UHI dome simulation, regional wind patterns, air pollution transport.

Microscale (Meters to Kilometers):
- **Focus:** Neighborhood, street canyon, or building-group level.
- **Physics:** Explicitly resolves (or models) the flow and thermal effects around individual buildings.
- **Used for:** Pedestrian thermal comfort, wind safety, detailed pollution dispersion, building facade heat transfer.

Urban modelling tools: Overview

MESO-SCALE

- Aims at atmospheric research and operational forecasting applications.
- Applications include real-time weather forecasting, data assimilation, parameterized-physics research, regional climate simulations, air quality modeling, atmosphere-ocean coupling, and idealized simulations

Weather Research and Forecasting (WRF)

Meso-NH – mesoscale non-hydrostatic model

mesoscale atmospheric model of the French research community

Australian Community Climate and Earth System Simulator (ACCESS)

MICRO-SCALE

Specialised Microclimate CFD Tool

Comprehensive model for urban surface-plant-air interactions, such as building physics, radiation exchange, and the cooling effects of vegetation, air pollutant dispersion

ENVI-met

- Paid
- Closed source
- GUI
- Neighbourhood scale

PALM4U

- Free
- Open source
- No GUI
- Neighbourhood and city scale

General CFD Tool

General purpose CFD for a wide range of physical phenomena, including chemical reactions, turbulence and heat transfer.

ANSYS FLUENT

OpenFOAM

Other

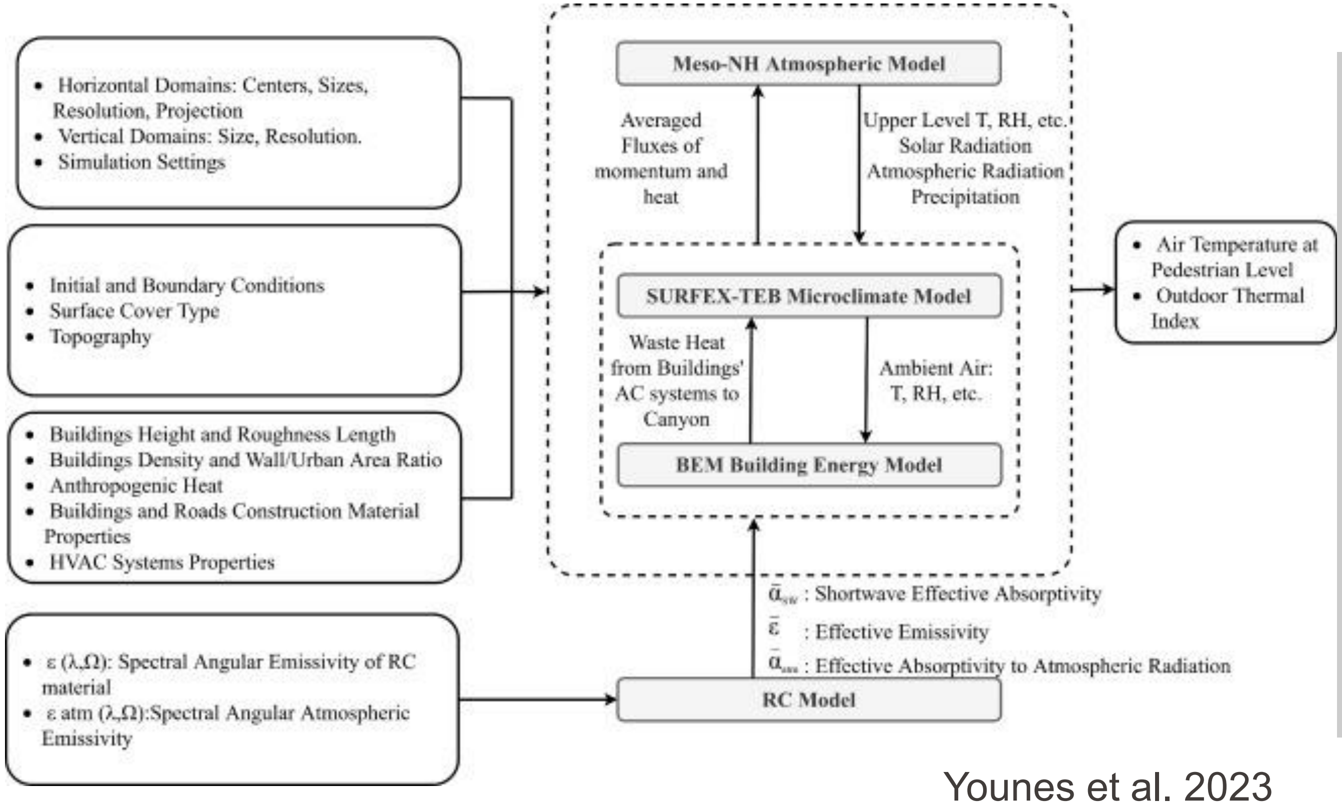
CITYSIM
Energy performance and neighborhood.

CITY ENERGY ANALYST
Urban energy system planning and sustainability analysis

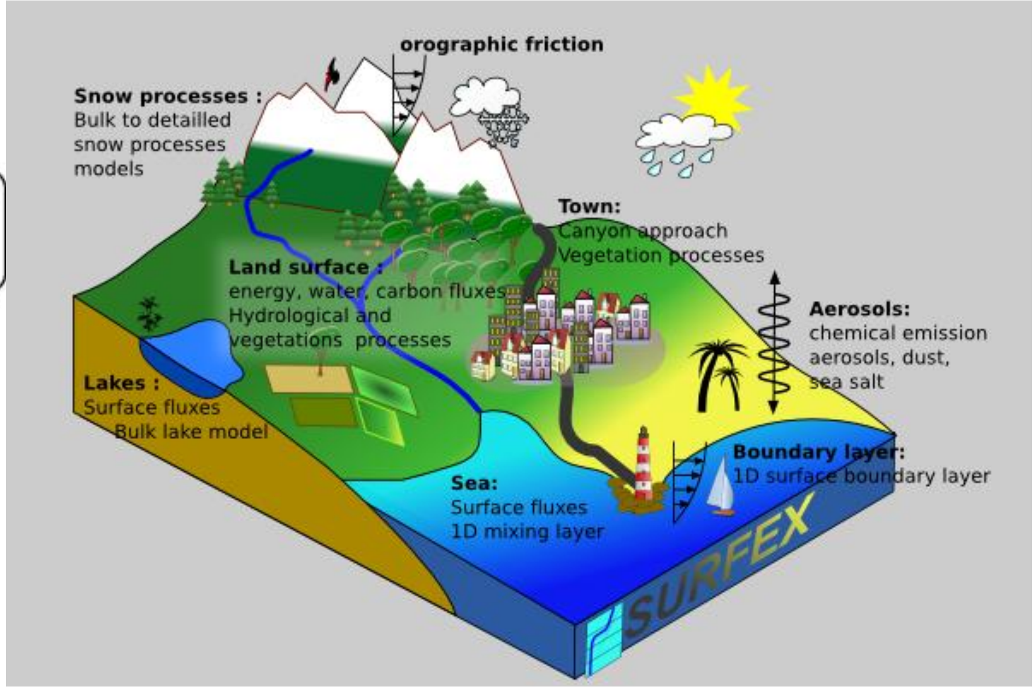
UMEP
Urban climate modelling and environmental prediction, for large scale application

and more…

Urban modelling: Mesoscale Models, Methods



Younes et al. 2023



SURFEX Model Documentation

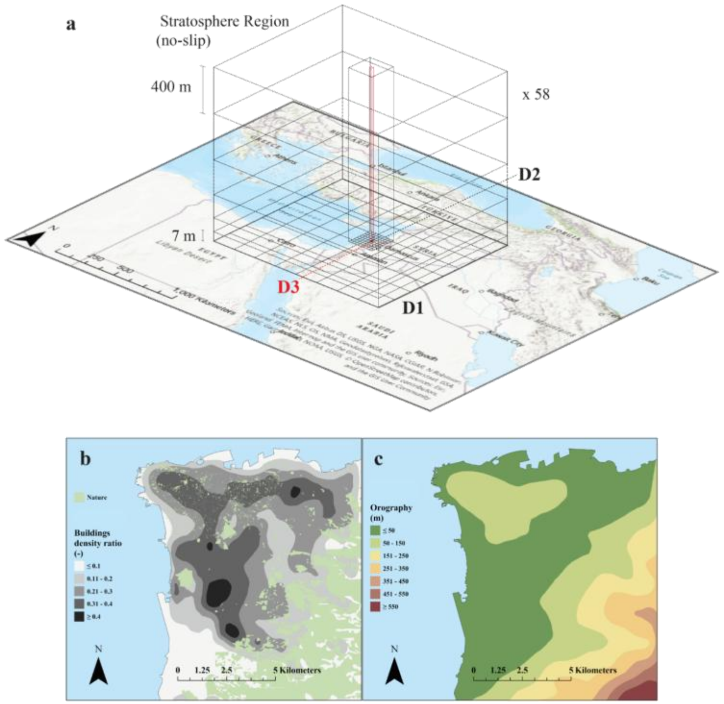
Urban modelling: Mesoscale Models (Atmospheric-Surface Models)

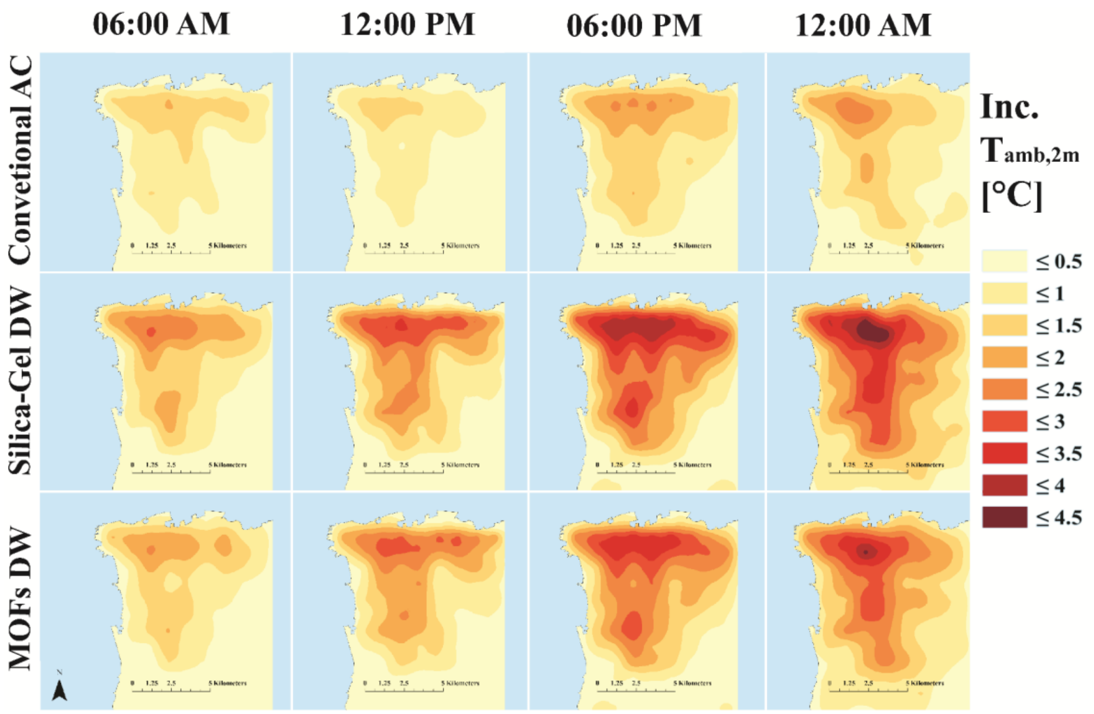
- **Purpose:** Simulating weather and regional climate modified by urban areas.

Example Tools:

- **WRF (Weather Research and Forecasting):** Among the most popular community models for atmospheric simulation. Widely used for UHI studies. It is often coupled with a UCM to represent the urban physics.
- **Meso-NH-SURFEX:** A sophisticated non-hydrostatic atmospheric model (similar to WRF) developed by French research community. It can be coupled to surface model SURFEX

Example Applications (Meso-NH, SURFEX):

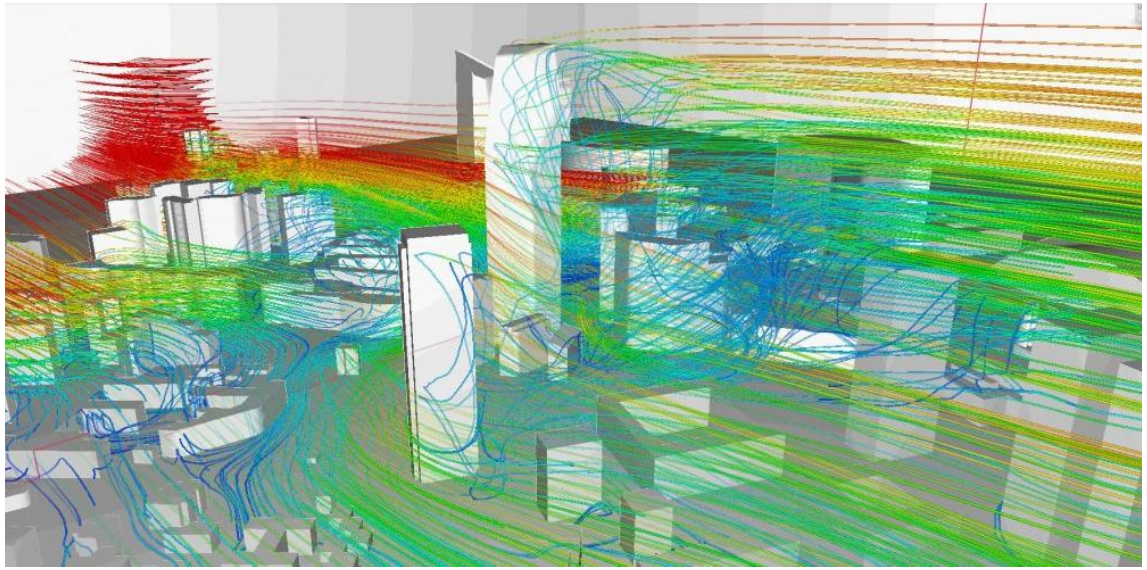


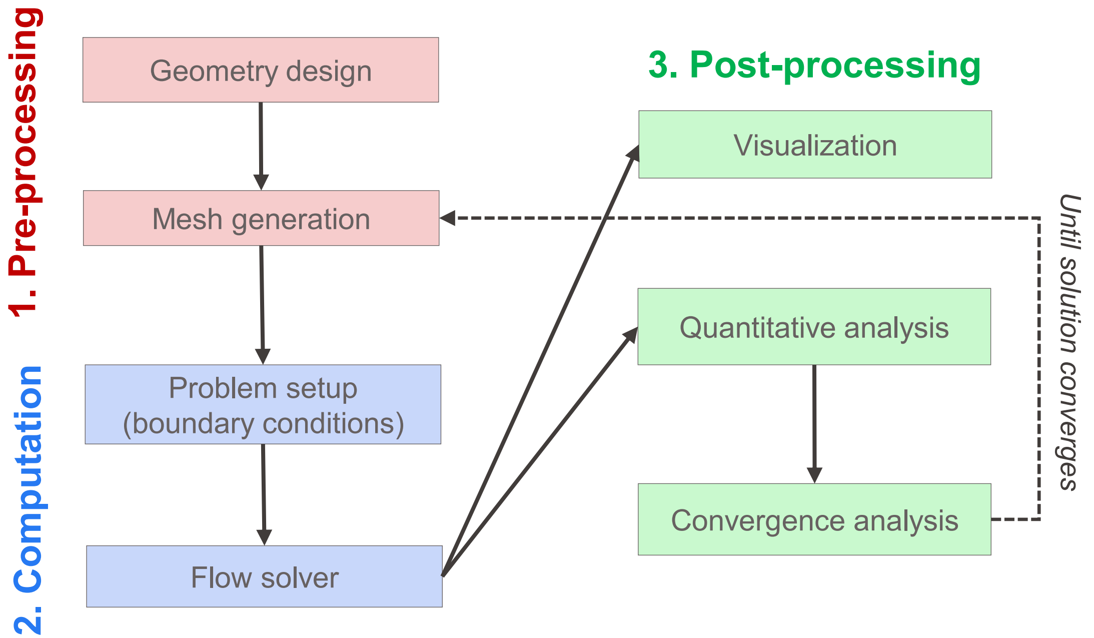


Younes et al. 2024

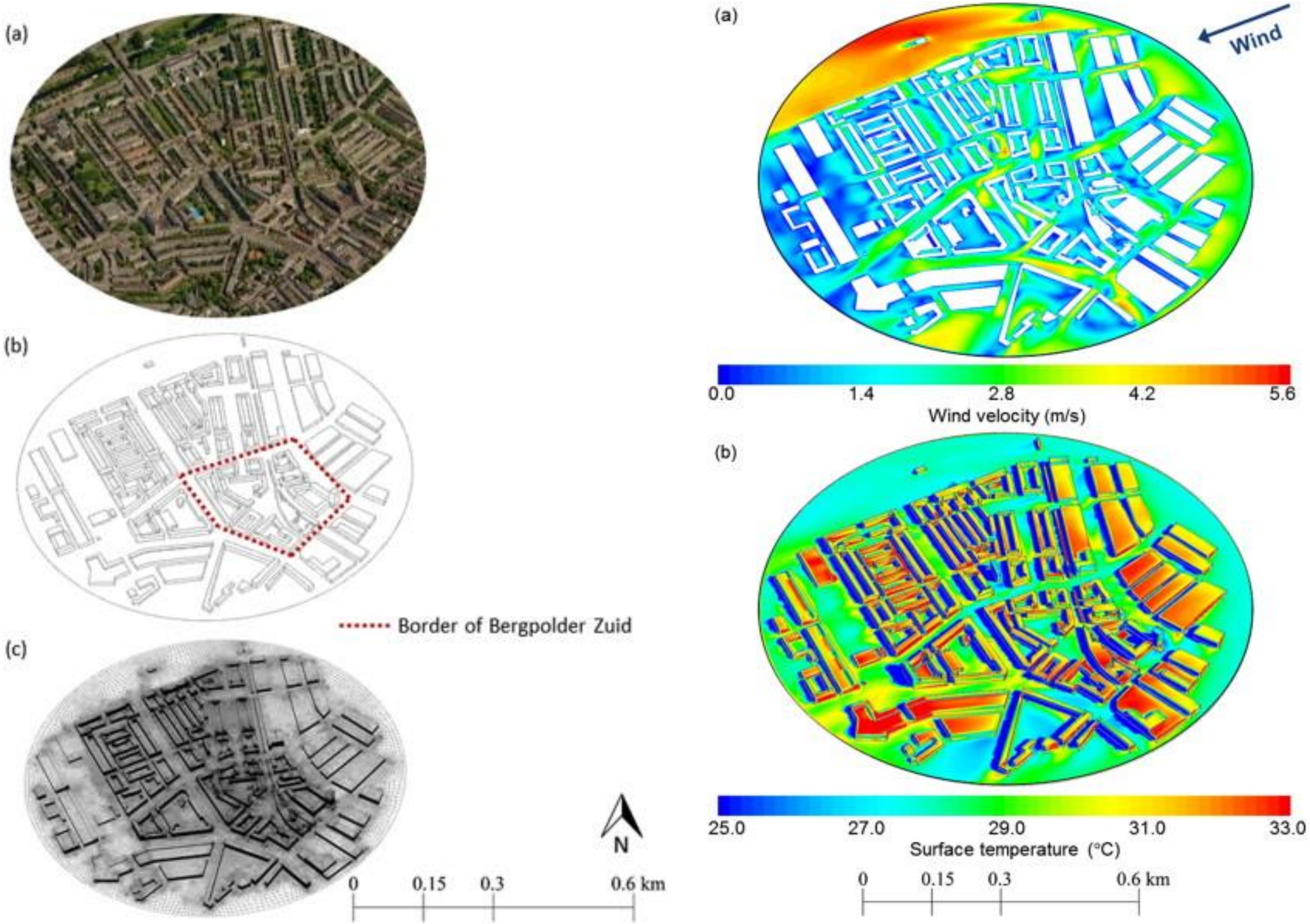
Urban modelling: Mircroscale Simulations/ Generic CFD

- **Computational Fluid Dynamics** (CFD) is a common **numerical method** used **to simulate flow dynamics.**
- The **finite volume method (FVM)** is commonly implemented in CFD tools (e.g. Ansys Fluent):
- 3 steps of CFD analysis: *pre-processing*, *computation*, and *post-processing*
- CFD is an efficient tool to replace *expensive* and *time-consuming experiments*, that gives physical information on the entire computed domain and that is *useful to perform* **parametric studies** and **optimization**





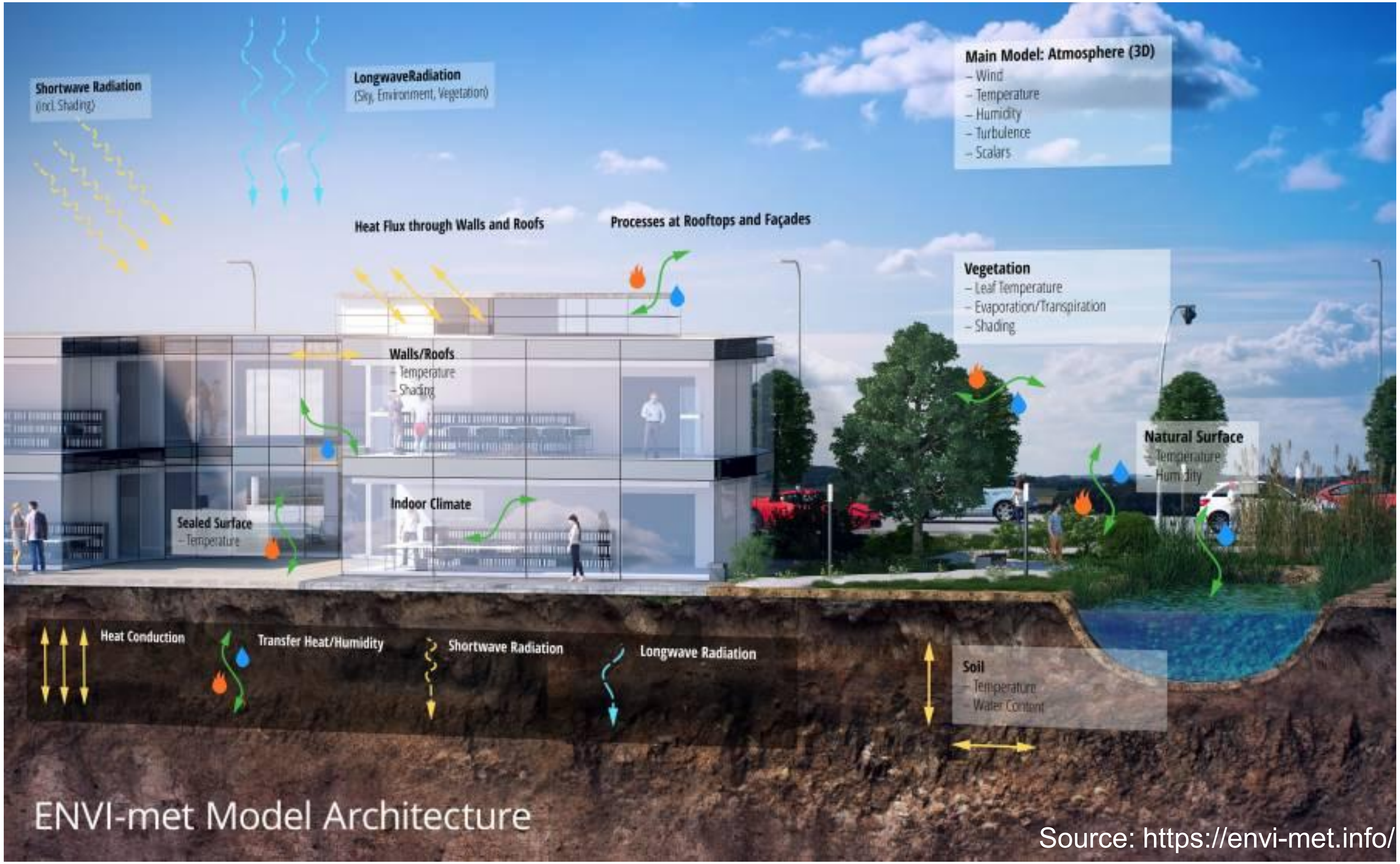
Urban modelling: Generic CFD Example



Toparlar et al. 2015

Urban modelling tools: Specialized Microclimate CFD

- **ENVI-met:** prognostic model based on the fundamental laws of *fluid dynamics* and *thermodynamics*



Source: https://envi-met.info/

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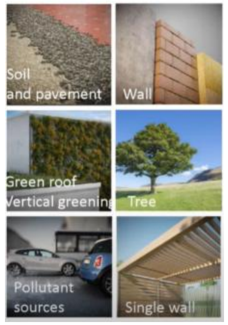
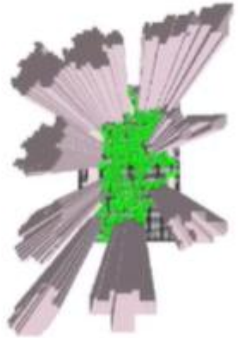
ENVI-met: Simulation workflow

Design concept
- 2D scaled sketch;
- Digital geometry in other 3D modelling software

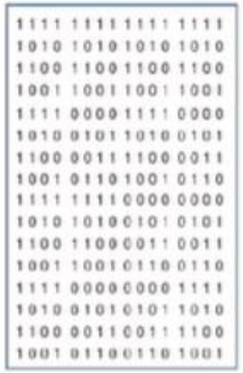


Material database
- Create material and specify thermal properties (heat absorption, transmission, reflection, emissivity, specific heat, thermal conductivity, density).
- Create wall, roof constructions (3 layers)

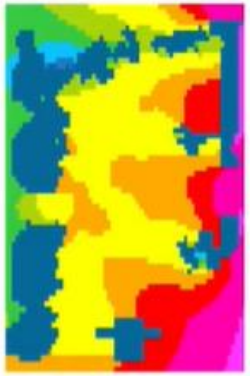


Digitise 3D model
Create model area, import background pic from step 1, model the study site (buildings with materials assigned, ground, vegetation, etc.)

Meteorological condition
- Download weather data (e.g., epw file)
- Create forcing files in *forcing manager*, inspect weather conditions of specific days and choose simulation period (drastic change of wind speed and direction can lead to simulation issues).

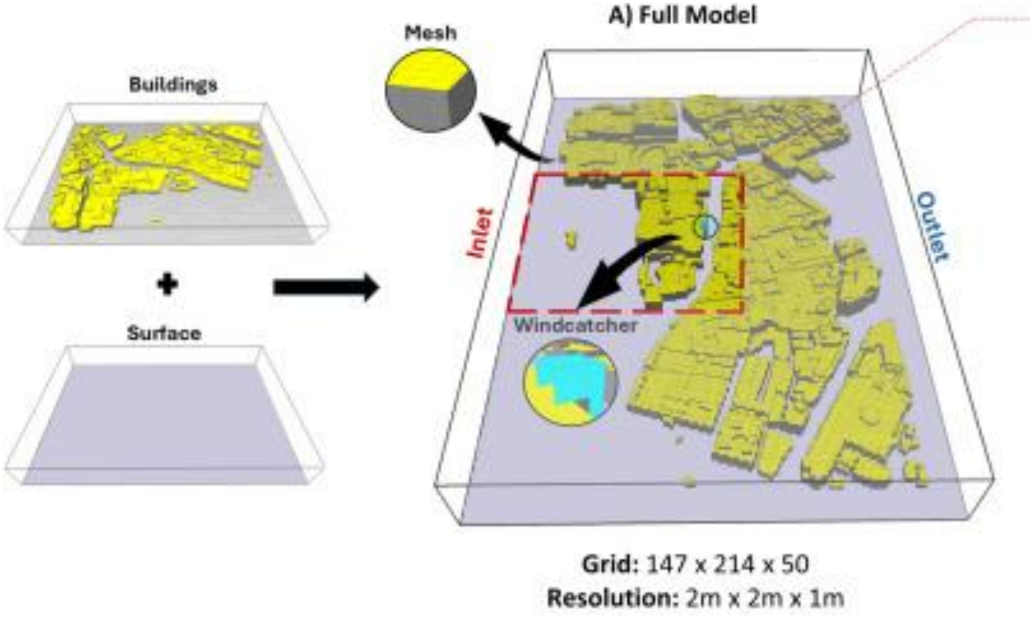


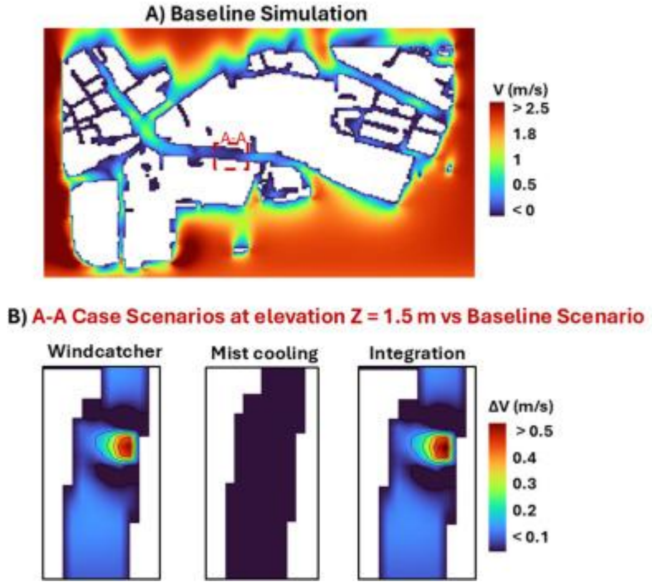
Simulation
- Create *SIMX* file in *envi-guide*, specify simulation settings.
- In *envi-core*, run simulation.

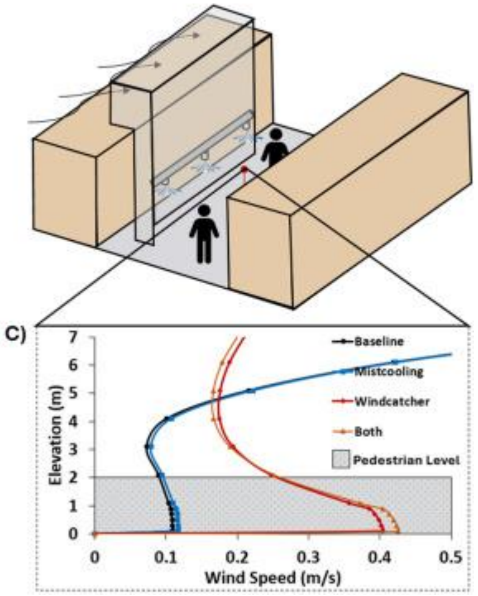


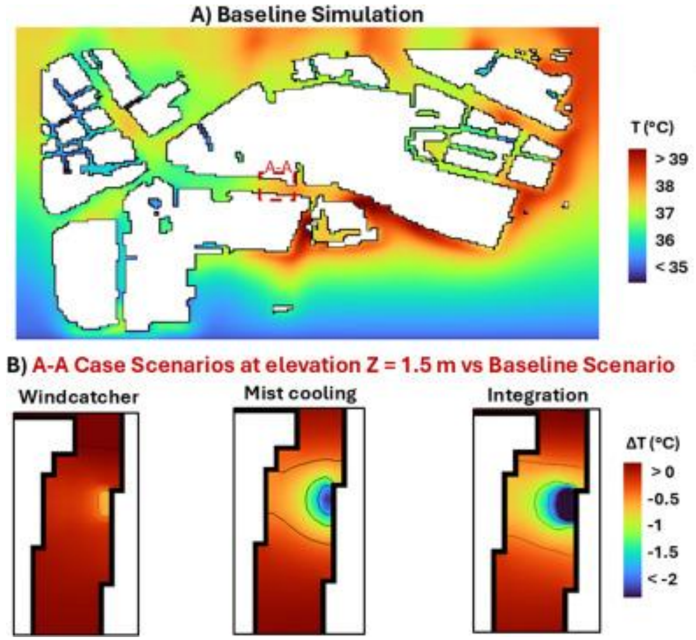
Visualisation
- Data exploration in *Leonardo*, or *QGIS, or import data – net CDF format to other data analytical tools (Python, R, excel…)*

ENVI-met: Example Study









Kachmar et al. 2025

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ENVI-met: Summary: Model Integration & Key Takeaways

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- Urban modeling involves a choice between **physical** (wind tunnel) and **numerical** (computer) methods.
- Physical models are limited by **similarity** requirements.
- Numerical models are categorized **by scale** (In context of urban climate mainly: Meso & Micro).
- **CFD** (Fluent, OpenFOAM) provides **high-fidelity flow physics**.
- **Specialized tools (ENVI-met, Palm4U)** are designed for specific urban questions like thermal comfort or energy use.
- **No "One Model to Rule Them All":** The choice of model is dictated by the question you are asking and the scale of the problem.

Thank you for your attention!

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Urban modelling: References

- T.R. Oke, G.Mills, A. Christensen, J.A. Vooght, Urban Climates, Cambridge University Press
- Kachmar, H., Younes, J., & Ghaddar, N. (2025). Effectiveness of outdoor windcatcher and mist cooling in mitigating urban heat and improving pedestrian thermal comfort. *Sustainable Cities and Society*, 106838.
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- Younes, Jaafar, Kamel Ghali, and Nesreen Ghaddar (2022). "Diurnal selective radiative cooling impact in mitigating urban heat island effect." *Sustainable Cities and Society* 83: 103932.
- Toparlar, Yasin, et al. (2015) "CFD simulation and validation of urban microclimate: A case study for Bergpolder Zuid, Rotterdam." *Building and environment* 83: 79-90.