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New tools for assessing personal exposure near urban air pollution hotspots

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7th International Symposium on Ultrafine Particles – Brussels, May 15th 2019

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Exposure Modelling: the basics

Emissions

COPERT
SYBIL
COPERT street level

→

Dispersion Modelling

→

Exposure ("external")

Concentrations (PN)
Sensitive receptors
Statistics/Indicators

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Exposure Modelling: the basics

Emissions

COPERT
SYBIL
COPERT street level

EZM Tools

Exposure ("external")

Concentrations (PN)
Sensitive receptors
Statistics/Indicators

Regional scale
Country scale
City scale
Block scale

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Exposure Modelling: the basics

Emissions

COPERT
SYBIL
COPERT street level

EZM Tools

Reference meteorology

Exposure (“external”)

Concentrations (PN)
Sensitive receptors
Statistics/Indicators

Regional scale
Country scale
City scale
Block scale

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Exposure Modelling: the basics

Emissions

COPERT
SYBIL
COPERT street level

5-year
10-year
20-year

EZM Tools

Reference meteorology

Climate Change scenarios

Exposure ("external")

Concentrations (PN)
Sensitive receptors
Statistics/Indicators

Regional scale
Country scale
City scale
Block scale

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EZM: main modelling components

MEMO, v. 7.0

- Non-hydrostatic prognostic mesoscale meteorological model
- Flexible nesting configuration
- Code is ported to a variety of HPC platforms

MIMO, v. 91

- RANS CFD model
- Fully configurable nonequidistant meshsize in all three dimensions and near obstacles

MARS-aero, v. 6.0

- Multi-layer chemical transformation and dispersion model
- Modular support for multiple chemical mechanisms
- Secondary Organics Aerosol module

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MARS-aero: chemistry and PM physics

- **Gas chemistry**
  - RACM (72 species, 234 reactions)
  - EMEP (66 species, 136 reactions)
  - KOREM (20 species, 39 reactions)
  - CBM-IV (47 species, 92 reactions)
- **Secondary PM**
  - Three-mode model
  - Internally mixed assumption
  - Na, H2SO4, NH4, HNO3, HCl, EC, OC, OTH (mainly mineral dust)
  - Aerosol number concentrations
  - Inorganics → ISOROPIA (sodium, sulfate, nitrate, ammonia, chloride, water)
  - Organics → SORGAM (with improvements)
    - ARO1,2 (aromatic), ALK1 (oxidization), OLE1 (oleine), ALPI1,2 (α-pinene), LIM1,2 (limonene)

EZM: an arsenal of Modelling Tools

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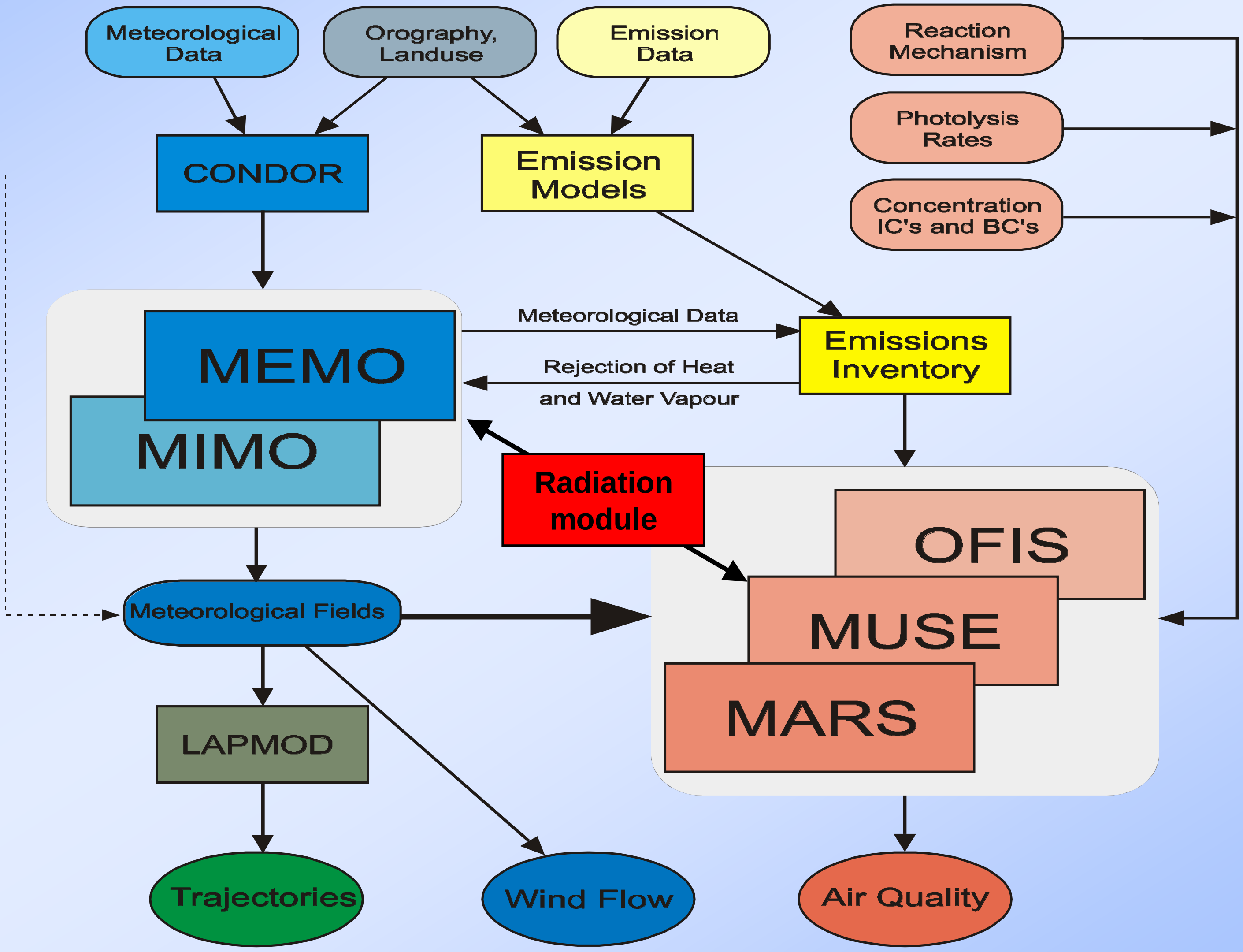

EZM+PALM LES

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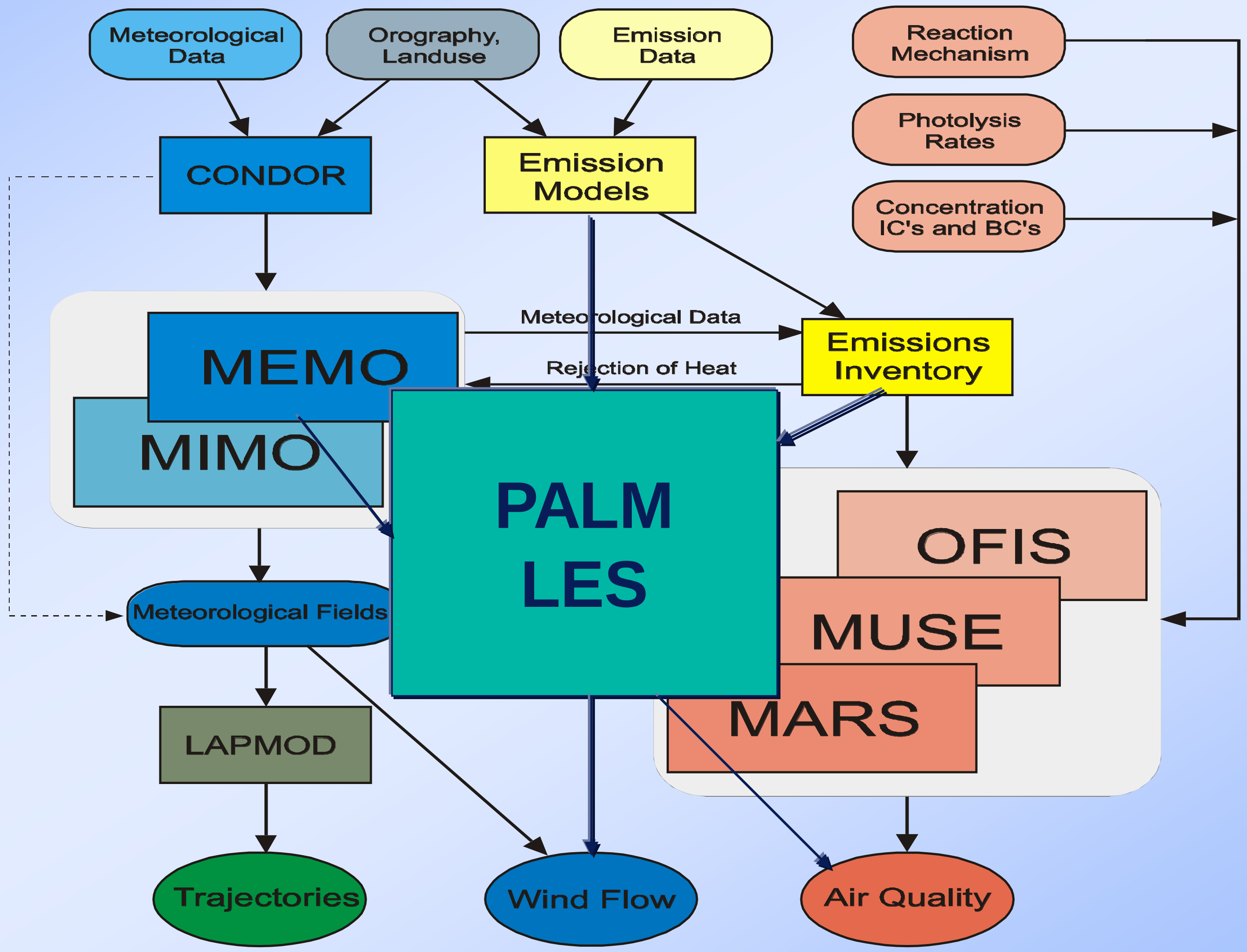

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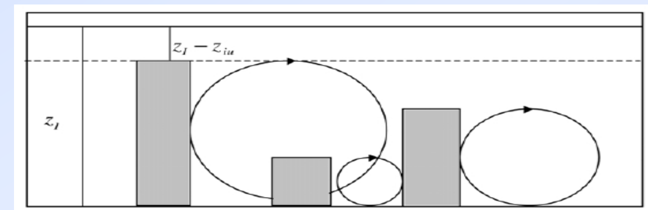
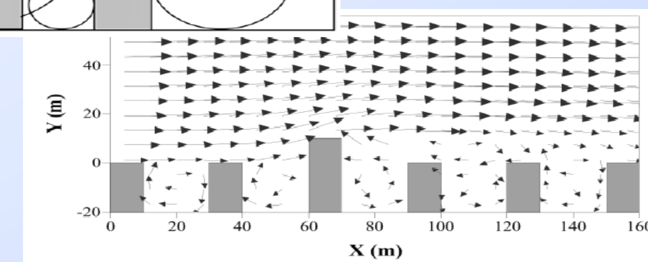
Hotspot assessment : a multiscale problem

- Mesoscale models can typically simulate atmospheric flows in the 20 – 500 km scale, providing reliable 3D meteorological fields for simulating pollutant transport, diffusion and chemical transformation in and around urban areas.

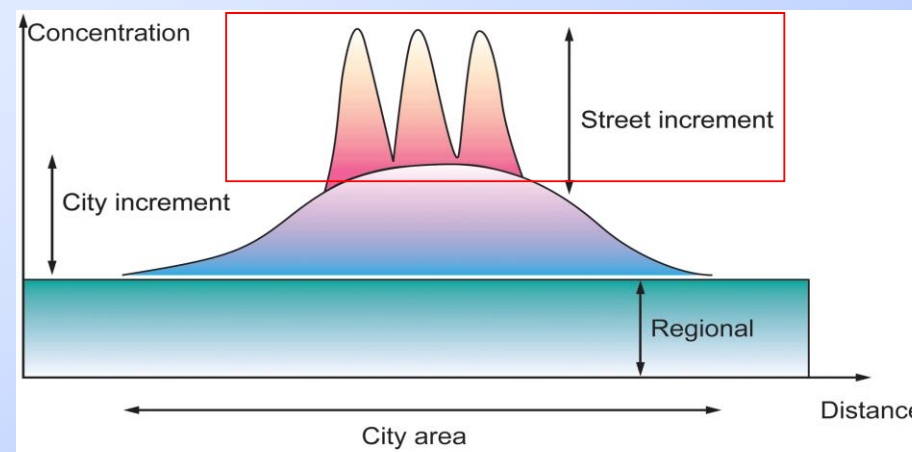
- These models cannot resolve urban canopy effects or explicitly take into account obstacle geometries.

- Hotspot exposure encompasses contribution from at least three spatial scales: a regional, a higher city-scale background, and local-scale increments.





Source: Masson, 2000



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Obstacles to multiscale modelling

1. Spatial scale gap → timestep gap → offline coupling

2. Chemistry combatibility → Aggregation (but online?)

3. Representativeness → How to treat point measurements

Integration: Air Quality management system

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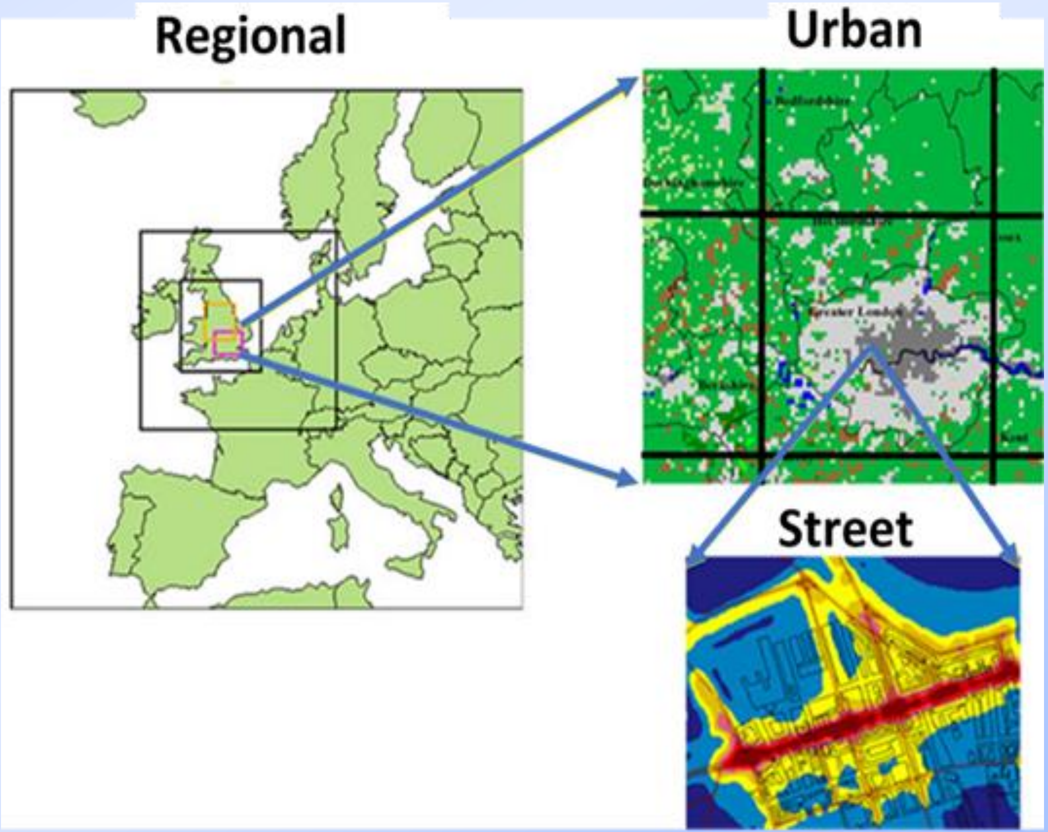
What it does

- Evaluate AQ in real-time and for the next day
- Regional down to street scale
- Emissions at different scale are taken into account
- Identify hotspots
- All major pollutants
- Impact assessment of (proposed) policy measures
- Customised coverage



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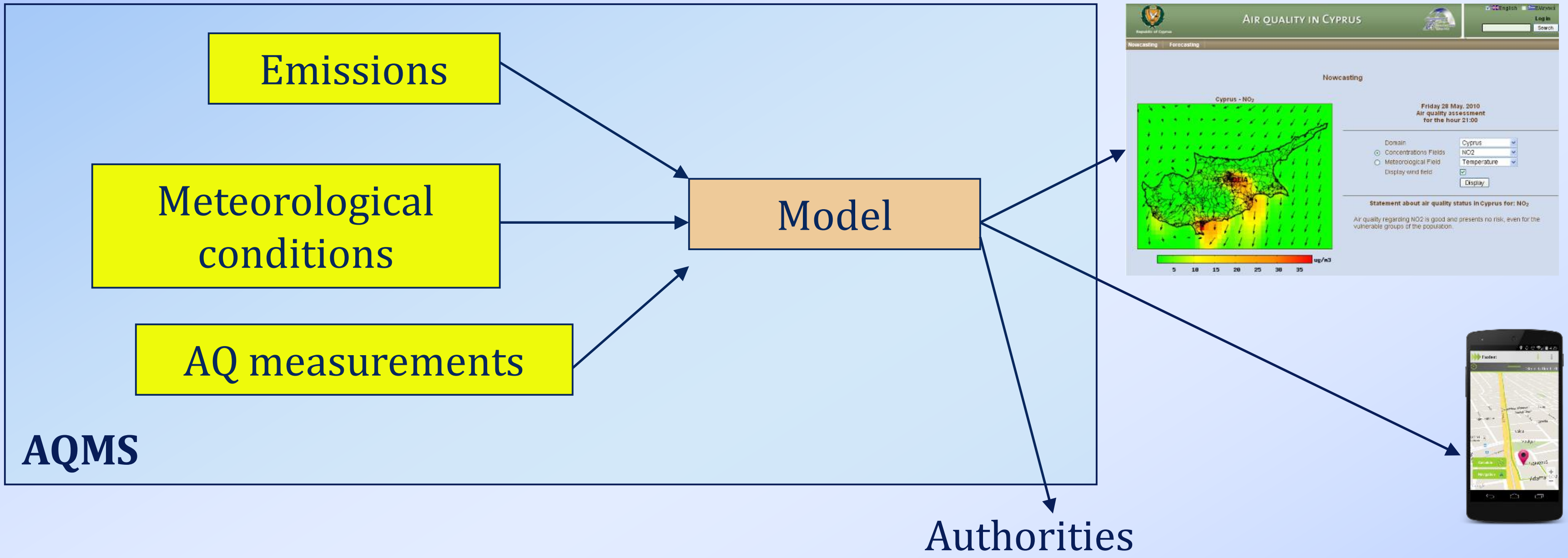
Operational Features



- Hourly AQ estimates (NOx, SO2, CO2, CO, PM, PN, BC) for the whole region and zoomed over streets, hotspots
- Informational messages about the air quality situation are automatically displayed on the webpage, can also be sent to smart devices (phones).

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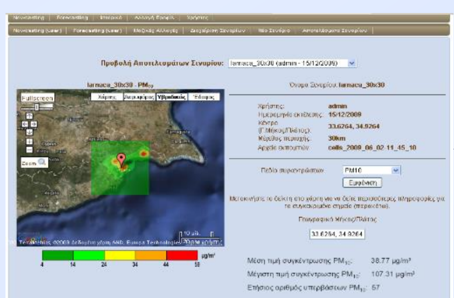
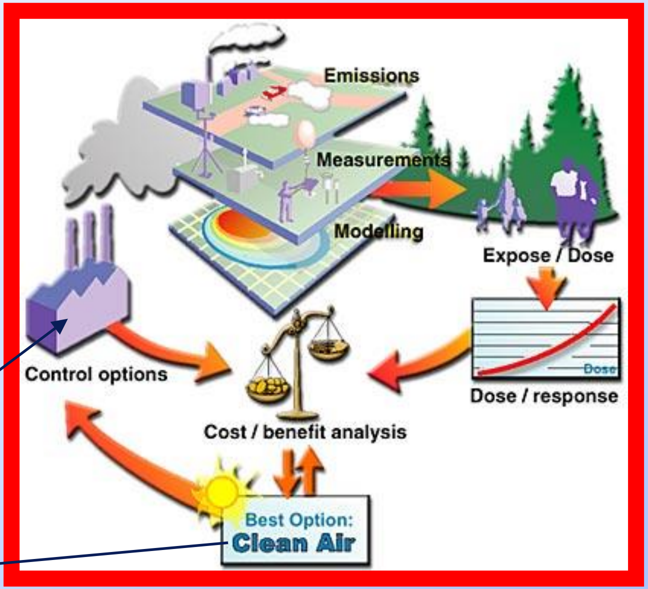
Scenario Assessment

- Various control options can be tested as emission scenarios
- Calculations performed for user defined areas are chosen with the aid of a friendly interface
- Display of the results in the form of maps and statistical indices



Decision Maker



Evaluation/Validation

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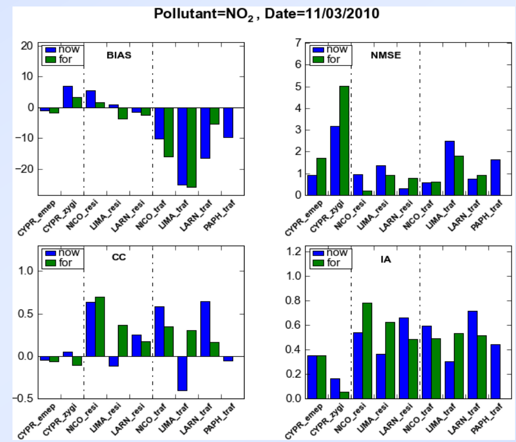
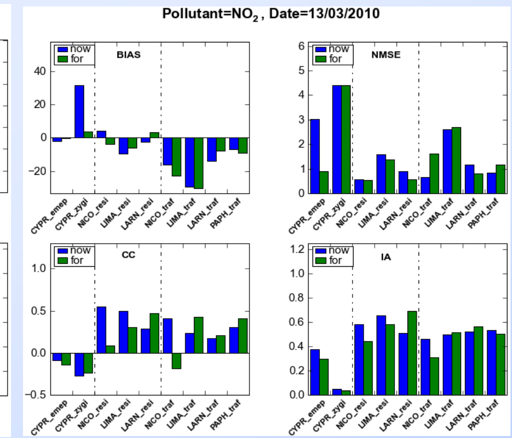
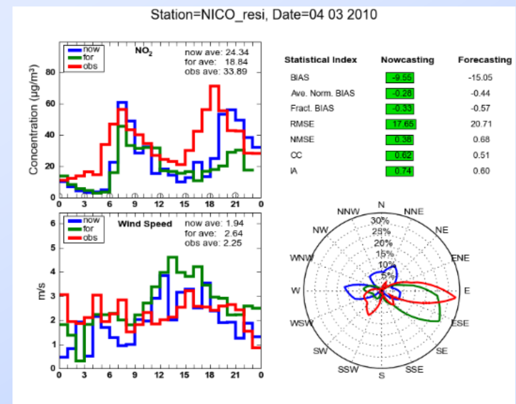
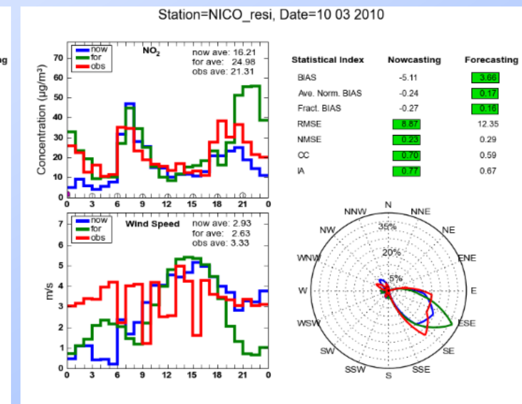
- A wide range of quality indicators are calculated according to the guidelines set by COST728, for the station locations and pollutants of interest
- Numerous charts are automatically provided for visually assessing the accuracy of the simulations in both nowcasting and forecasting modes
- Validation charts for the meteorological parameters are also provided









Solution A: semiempirical increment models

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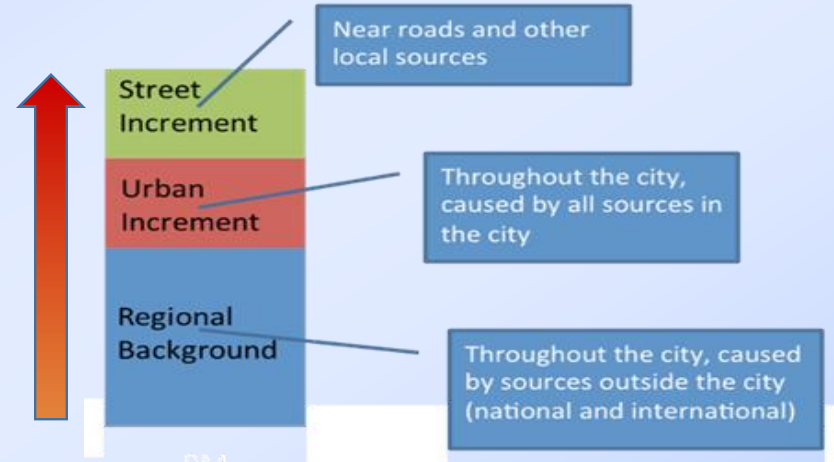
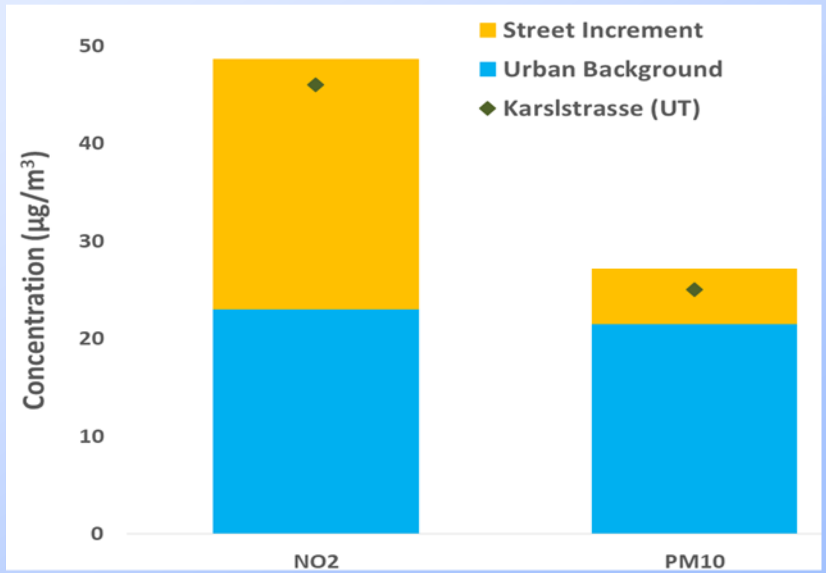
- An approach allowing the operational assessment of urban and local scale air quality without the need of detailed input data.
- The method is based on the efficient calculation of concentration increments on top of the regional and urban background concentrations, respectively.
- Core elements: functional relationships between local meteorological parameters, urban and street geometrical characteristics and emissions, constructed on the basis of measured increments in representative locations.
- 3 steps:
  - ✓ Selection of urban background pairs
  - ✓ Multiple regression analysis
  - ✓ Calculation of time- and location-depended increments



Application: Augsburg, Germany



Solution B: Explicit mesoscale-microscale coupling

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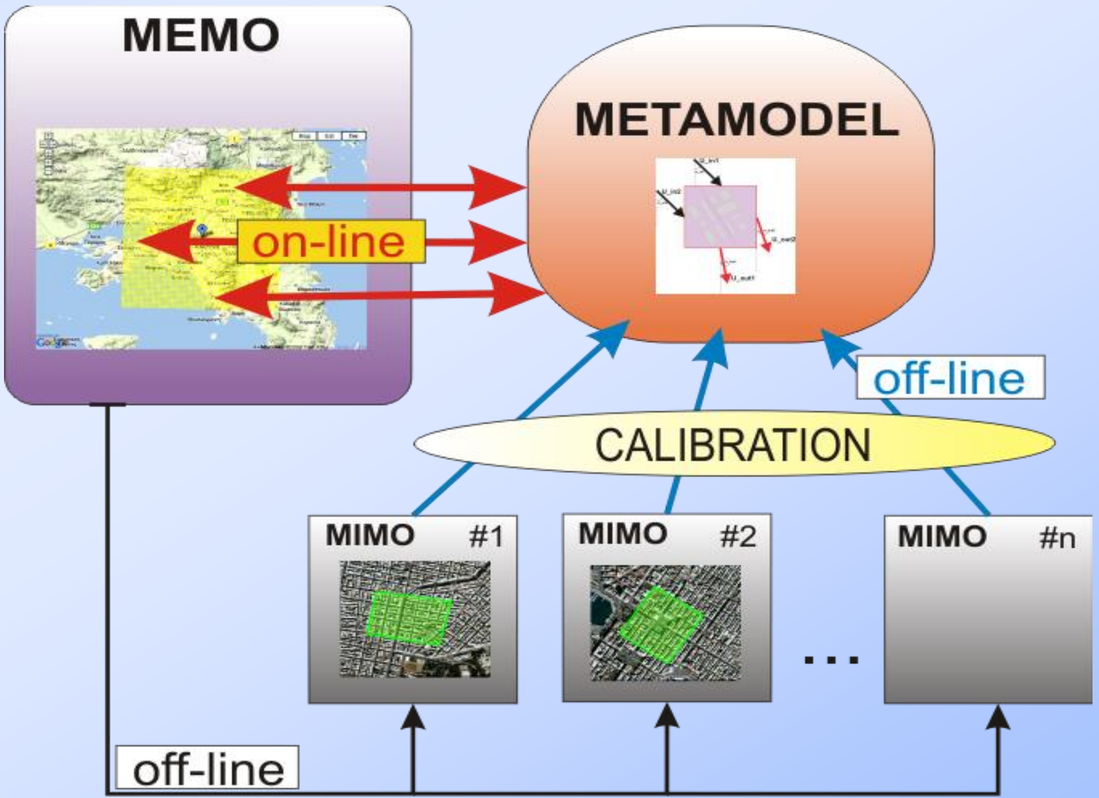
- The calibration-application process can be applied iteratively, in order to increase accuracy of the mesoscale simulation
- Convergence is usually achieved in less than 3 iterations



Solution B: Explicit mesoscale-microscale coupling

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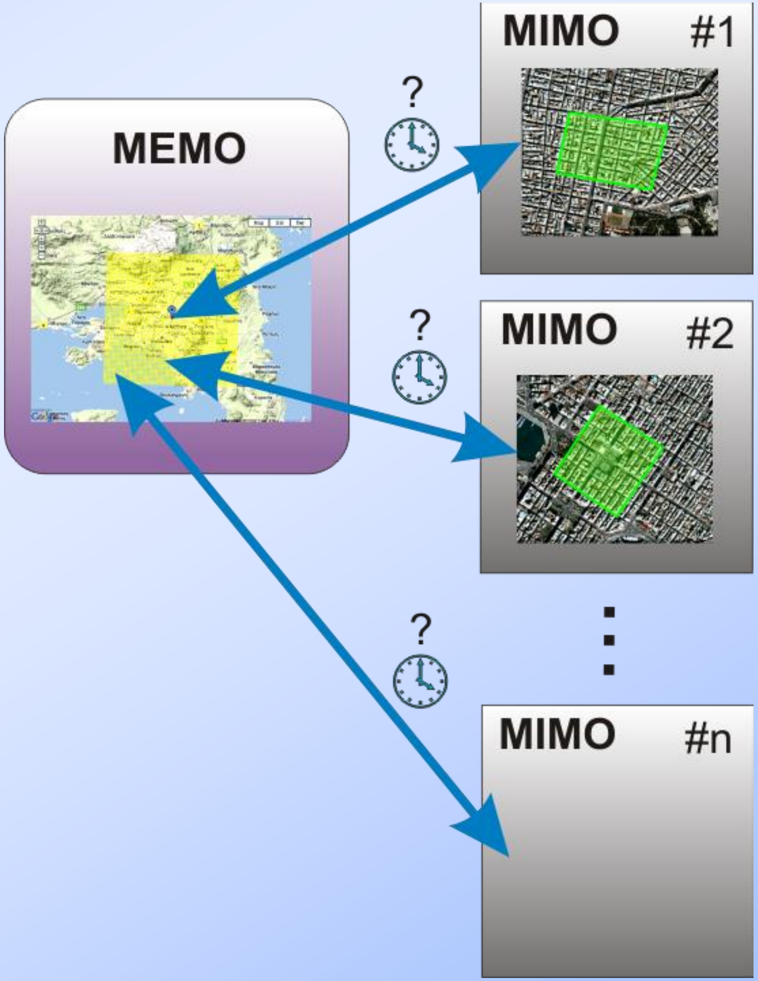
- Big spatial **scale mismatches**:
  - mesoscale: ~100 - 300 km
  - microscale: < 4 km
- The selected microscale domain should be **representative** (geometry, orientation, etc.) of the larger urban area
- "One-way" → **Cannot** estimate the effect of the microscale domain **on the mesoscale flow** (e.g. the combined effect from hundreds of urban cells)



Solution B: Explicit mesoscale-microscale coupling

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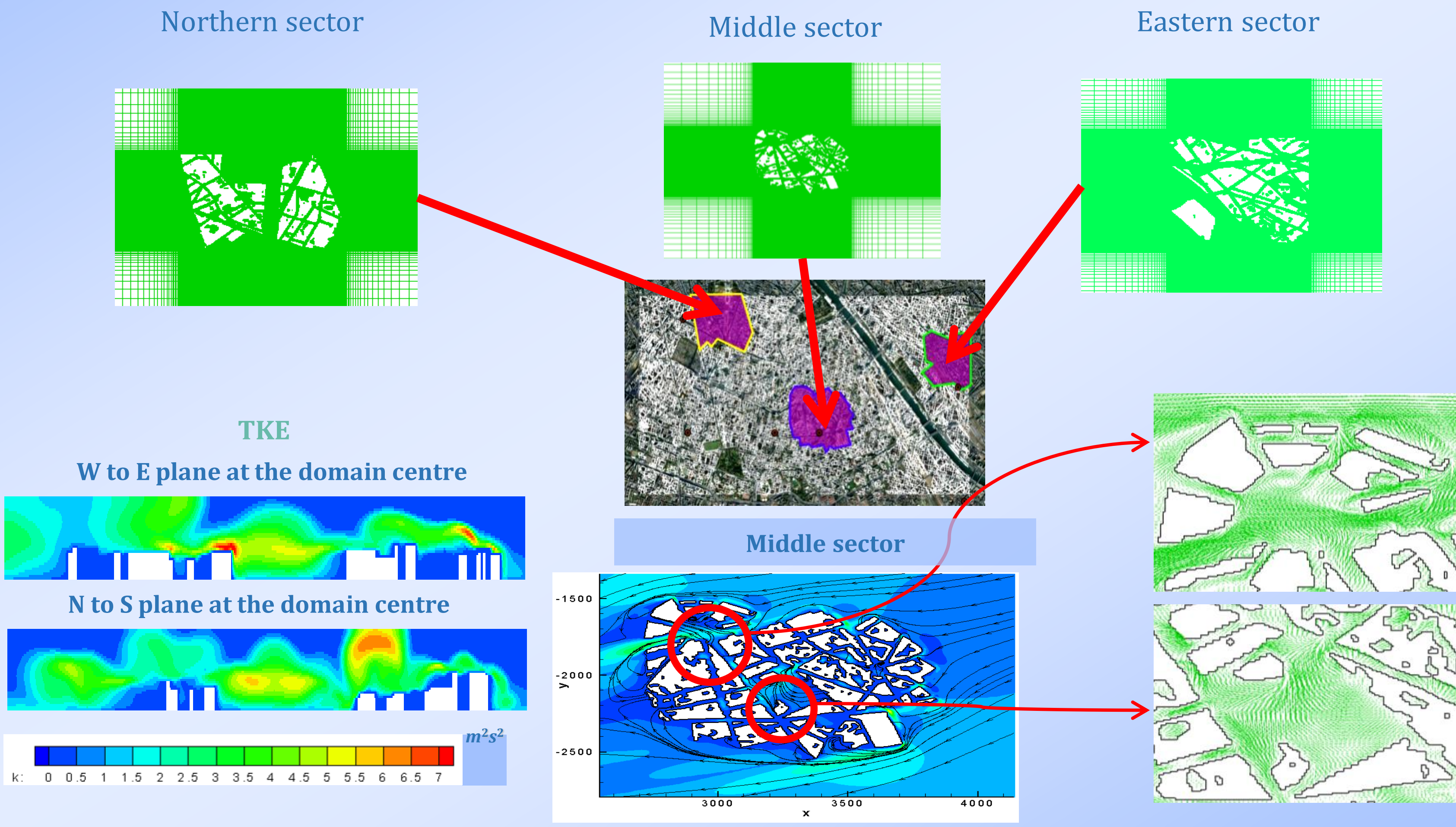

Test application in Paris, France

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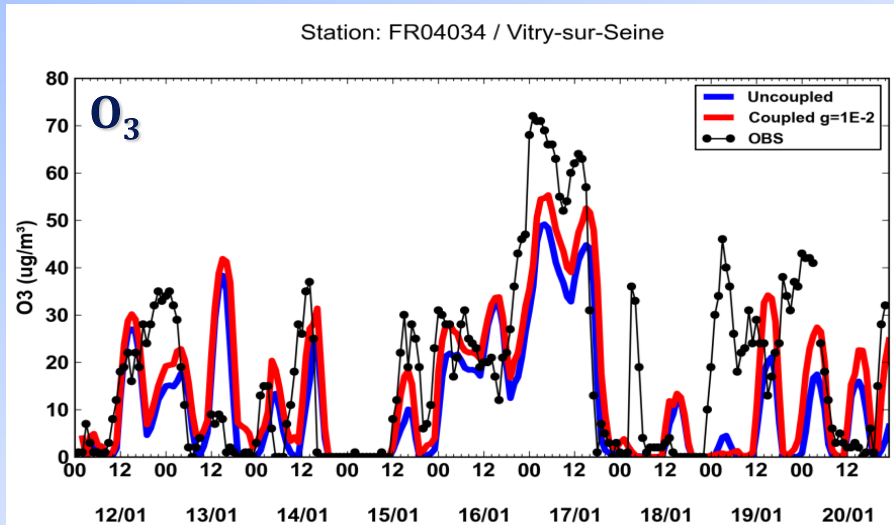
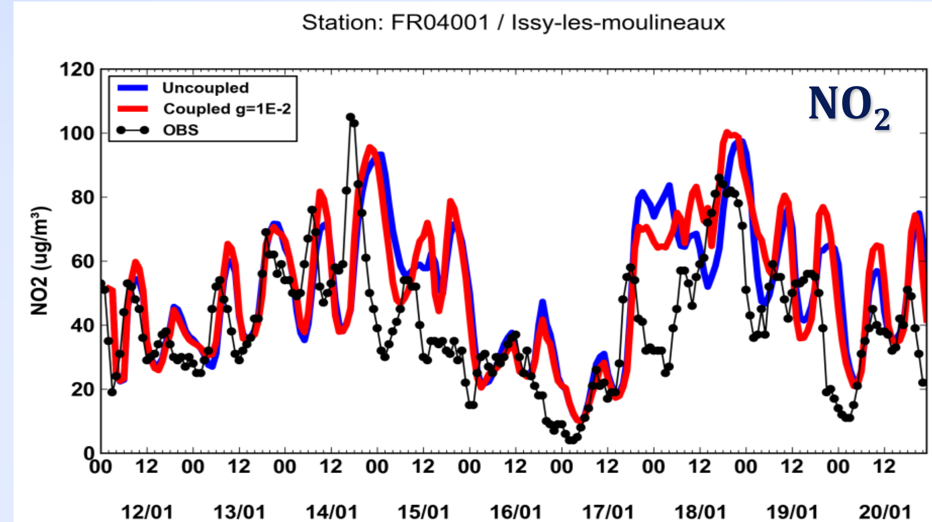
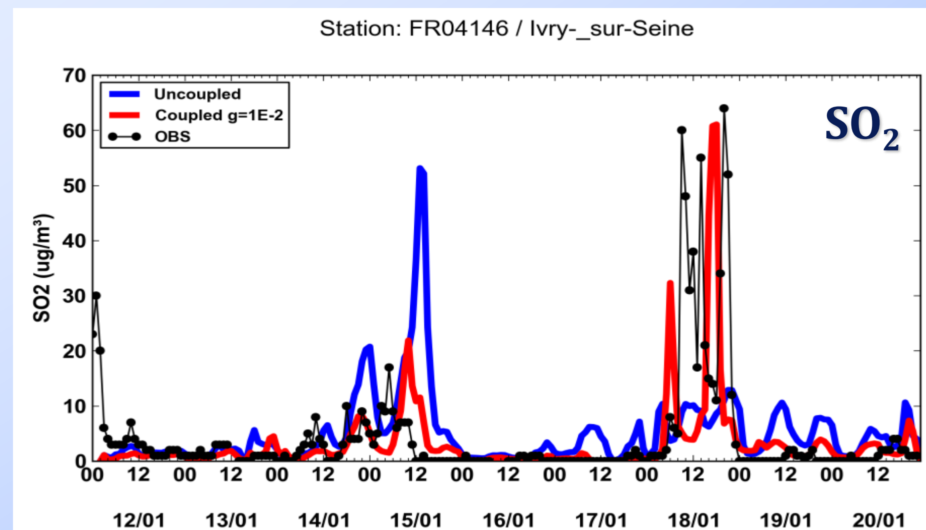
Solution B: Explicit mesoscale-microscale coupling





- **O_3 :** coupling improves bias
- **NO_2 :** Coupling improves bias and correlation
- **SO_2 :** significant improvement on background peaks



Test application in Paris, France

Solution C: Assimilation of data from AQ sensors

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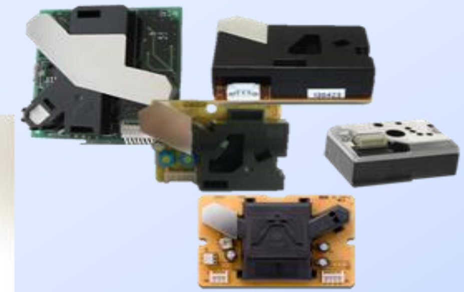
Source: SmartAQNet project



Standard (gravimetric)	Professional (mostly optical)	Consumer (mostly optical)	Low-Cost (optical)

	Tradeoff	
accurate	↔	noisy
stable	↔	unstable
expensive	↔	cheap
low temporal resolution	↔	high temporal resolution
delayed	↔	low latency
large	↔	small
static	↔	mobile

Solution C: Assimilation of data from sensors

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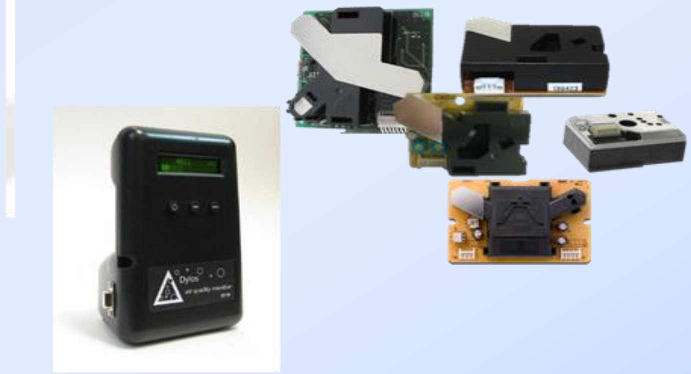
Advantages

- Low installation and maintenance cost
- Large number, better spatial coverage
- Flexible in placement
- Can be incorporated in IoT networks!
- If portable: measure personal exposure!



Consumer (mostly optical) | Low-Cost (optical)

Shortcomings

- Systematic error (mainly "drift")
- Sensitivity to environmental parameters
- Difficulty in spatial interpretation

AQMS models can mitigate these

Solution C: Assimilation of data from sensors

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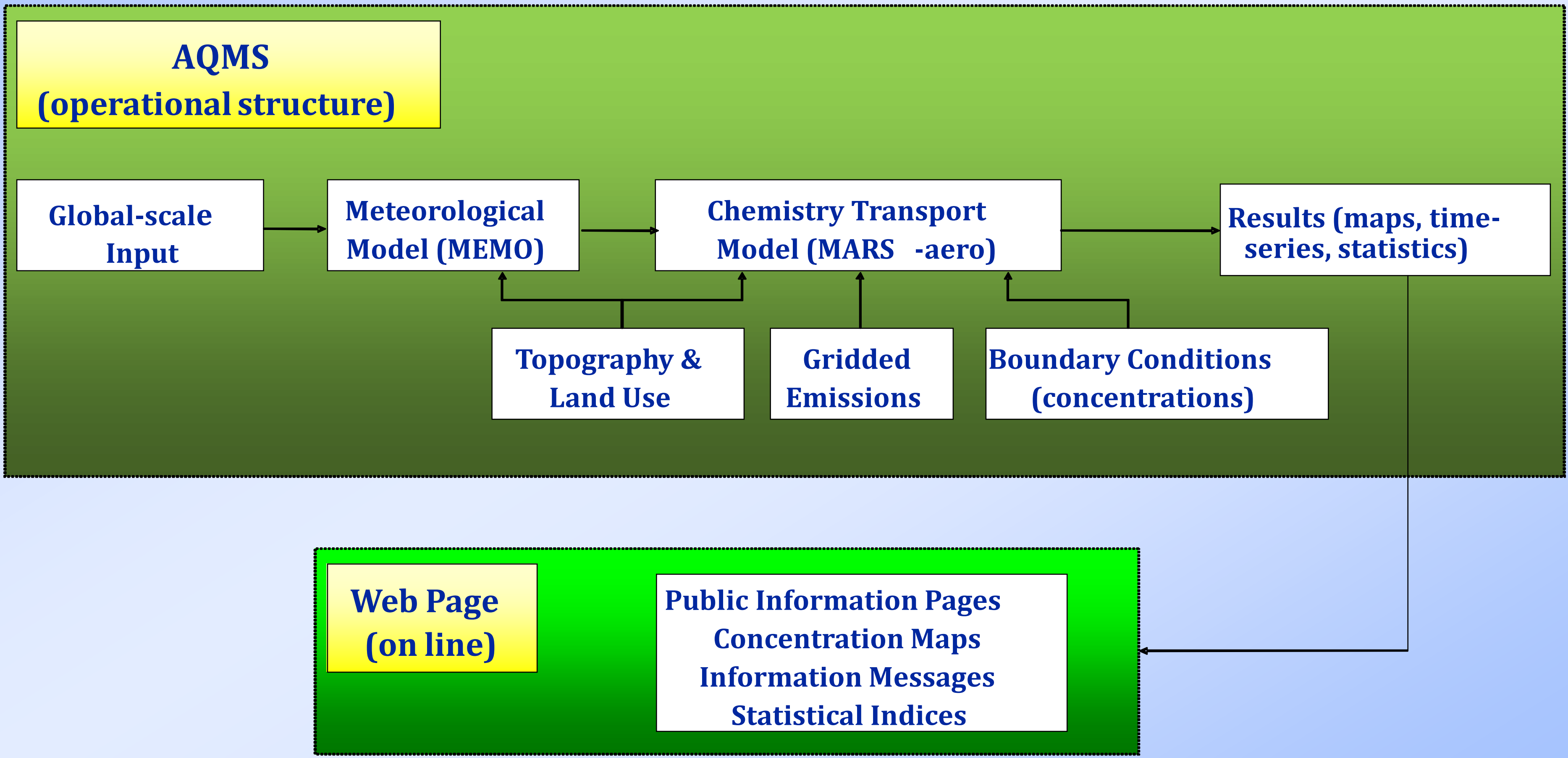

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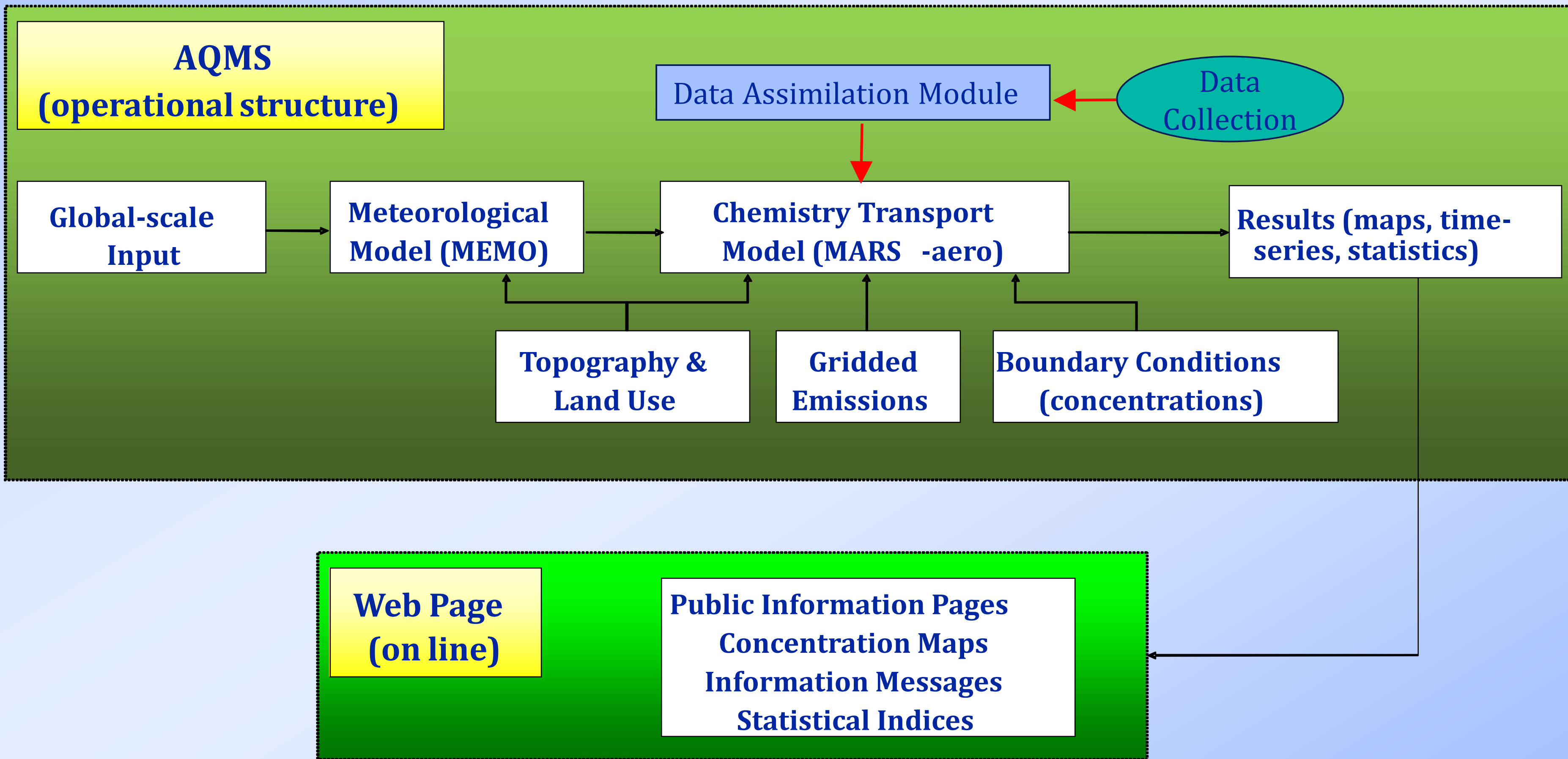
Solution C: Assimilation of data from sensors



Solution C: Assimilation of data from sensors

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Data Assimilation Module

1. Transfer of concentration data
2. Timebase checking, rejection of out-of-sequence data
3. Sanity checking: ranges (species-dependent), derivatives, spatial correlation
4. Classification (regional background, urban background, street-scale) and normalisation
5. Calculation of numerical tendencies (forcing terms)
6. Spatial "smearing" of tendencies
7. Incorporation of tendencies in the dynamical terms and step integration
8. Extraction of corrective terms, to be used in next assimilation/integration steps

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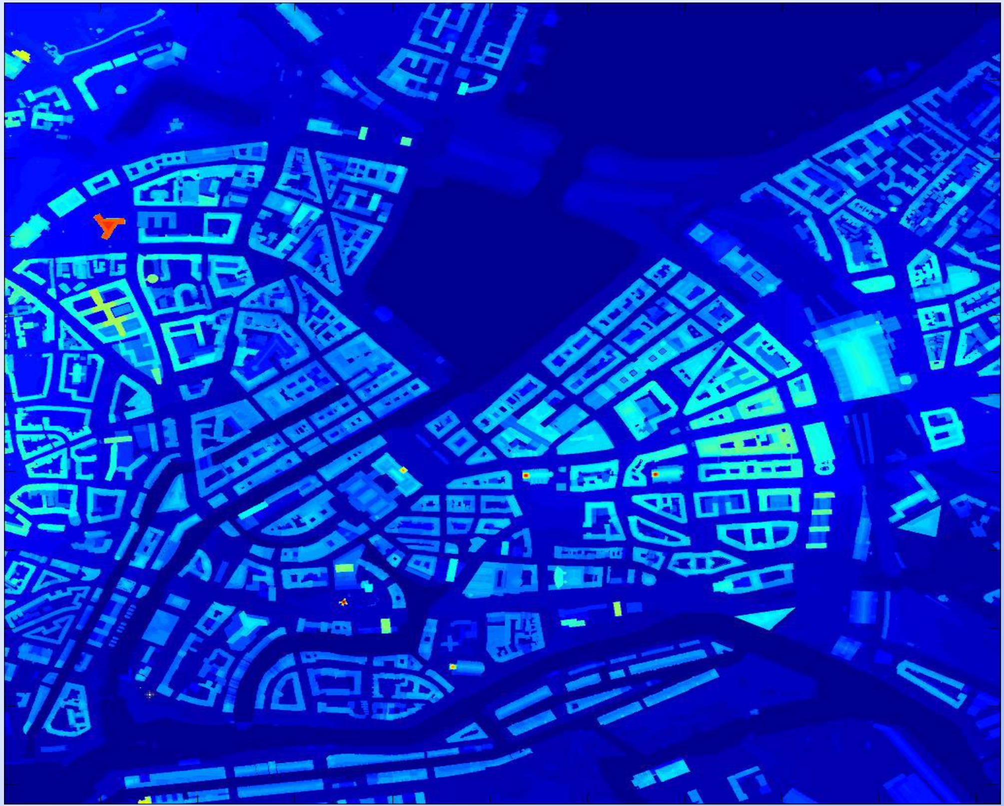
PALM-LES: A flexible solution for smaller scales

- The Atmospheric Boundary Layer (ABL) is solved simultaneously with the small-scale street-canyon turbulent events
- Advantages:
  - Highly turbulent flows can be simulated - simulations which capture the turbulent motion within streets can be performed
  - Multi-scale interactions resolved via self nesting



PALM-LES: A flexible solution for smaller scales

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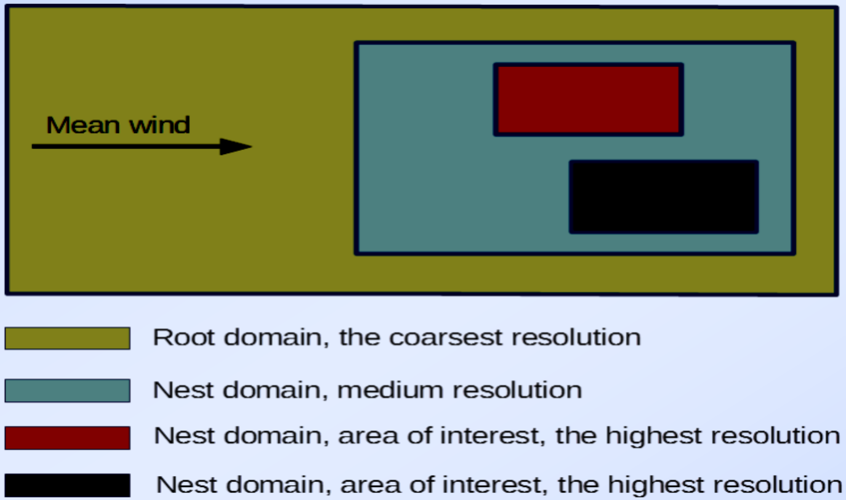
Self nesting

- ❑LES of wind flow in is a multi-scale problem
- ❑High enough resolution for a sufficiently large domain is usually too expensive → resolution must be concentrated to the area of principal interest
- ❑Model nesting is the only way to concentrate resolution to the principal area of interest as we gain from both fast solver and spatially varying resolution!



- ❑ The system of nested domains consists of the root and nest domains
- ❑ Nests can have their own nests and so on (cascading domain arrangement)
- ❑ Cascading and parallel nests can co-exist in the same run
- ❑ All nests must lay inside their parent model domain

PALM-LES: A flexible solution for smaller scales

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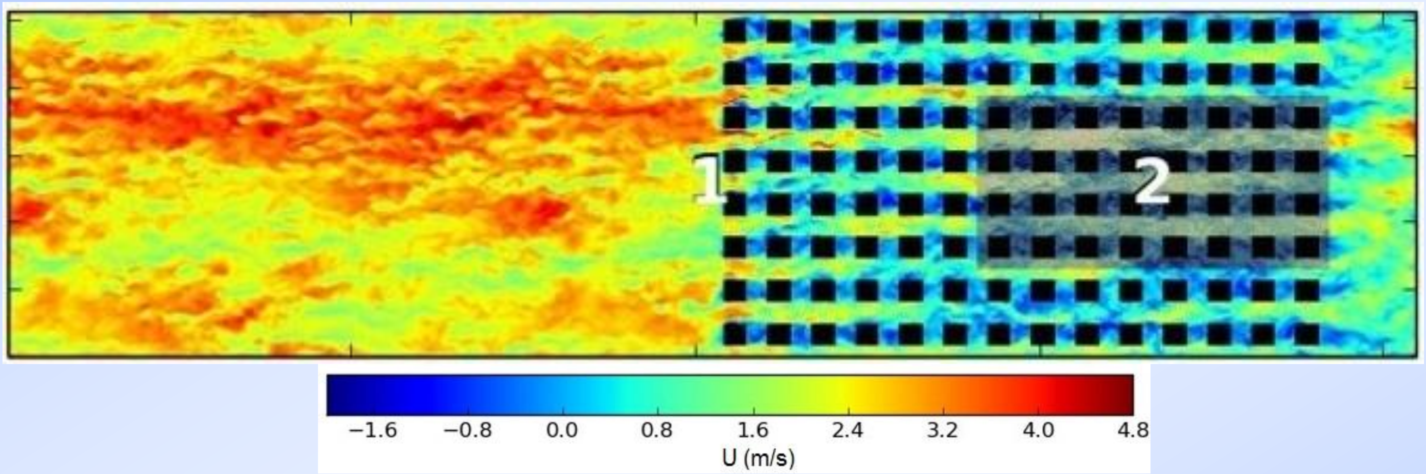
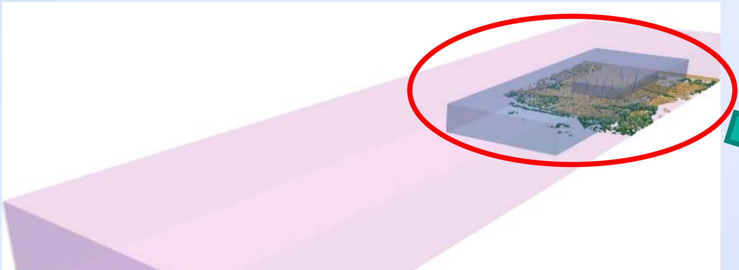
Functional testing of an array of cubes approximating buildings: success!



Example of PALM LES application in real city



Presence of vegetation can be accounted for

Leibniz Universität Hannover

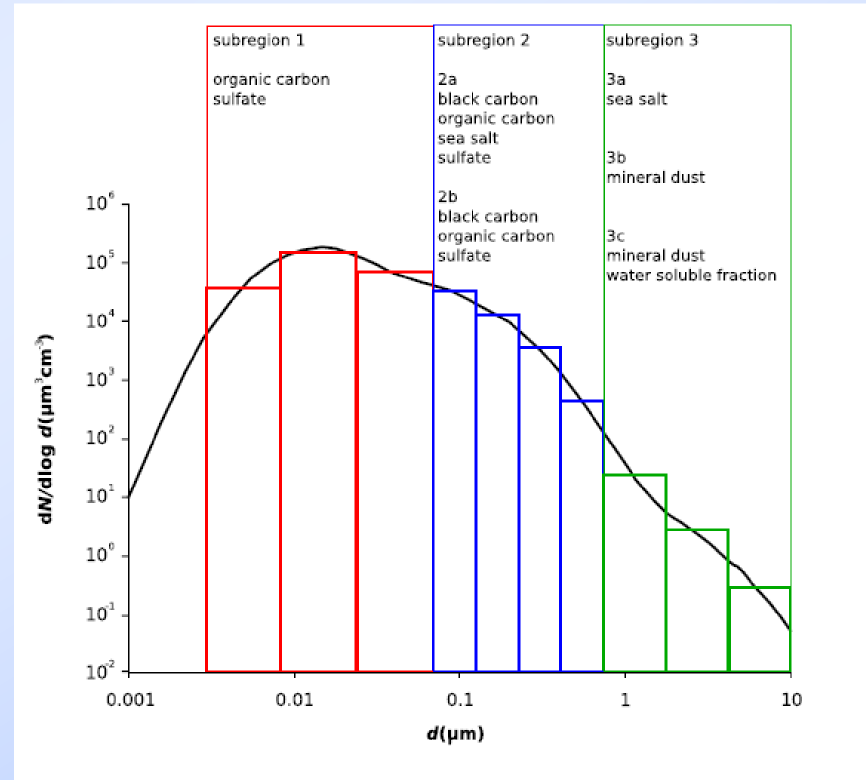
KIT Karlsruher Institut für Technologie

Chemistry and PM physics treatment in PALM

https://palm.muk.uni-hannover.de/trac/wiki/palm4u#chem

- A fully "online" coupled (Baklanov et al., 2014) chemistry module
- For the description of gas-phase chemistry the latest version of Kinetic Preprocessor (KPP 1) version 2.3 has been implemented into PALM-4U
- Fortran source code can be generated directly from a list of chemical rate equations, a special preprocessor automatically generates interface routines between the generated modules and PALM.
- A more complex chemistry module is available for the RANS mode
- A strongly simplified chemistry mechanism is available for the LES mode

SALSA – a Sectional Aerosol module for Large Scale Applications



. Schematic of the division of size distribution into subranges and sections in the aerosol SALSA.

Kokkola et al., 2007

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Conclusions and final thoughts

- Hotspot exposure (external) modelling is a multiscale problem
- Significant technical obstacles in “naïve” coupling
- Recent developments in tools/methods show that the problems are not intrinsic
- Online coupling (including chemistry) has become feasible
- Integration of modelling tools provides benefits, also for validation
- Data from inexpensive sensors: added value under certain conditions
- Progress in tailpipe-to-roadside modelling (inc. work in DOWNTO10 project, http://www.downtoten.com)

Thank you for your attention!
URL: http://aix.meng.auth.gr

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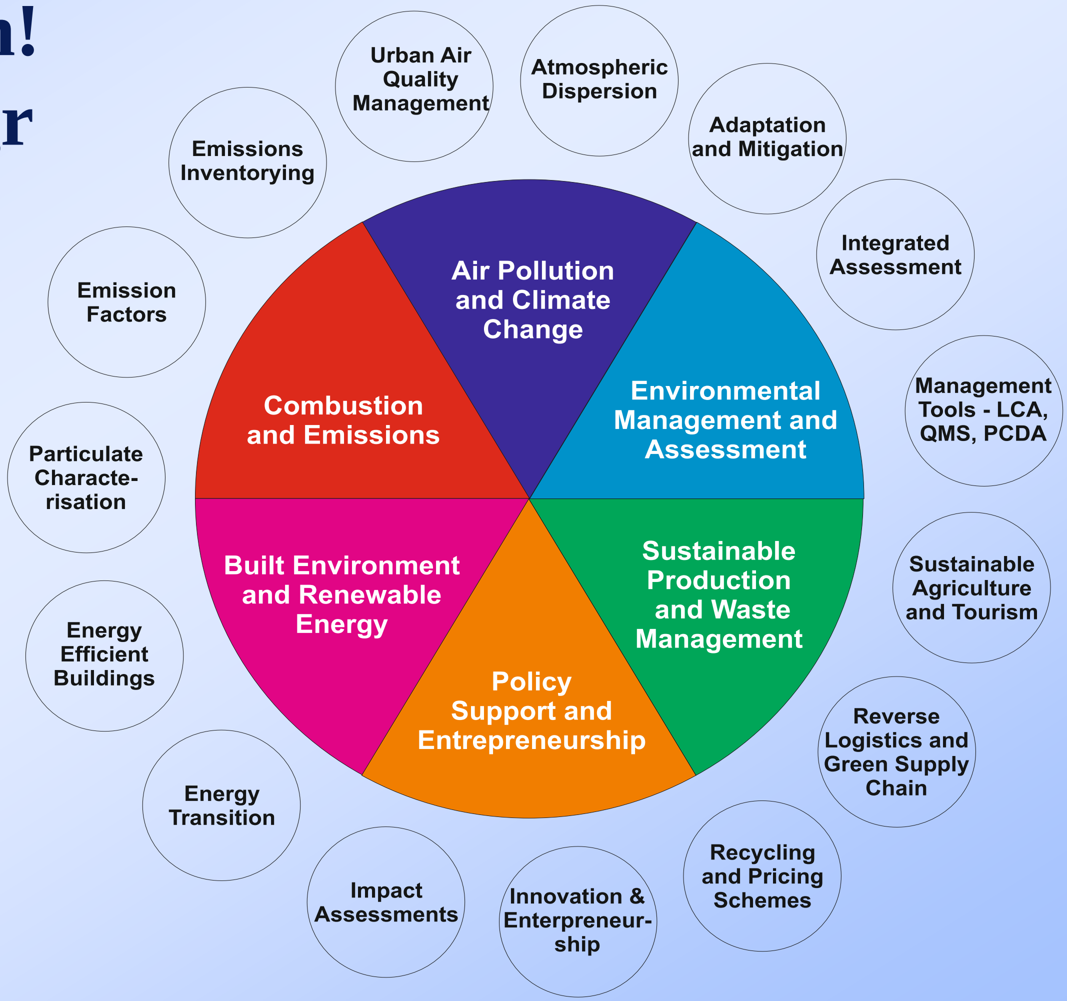
Main Research Topics:
- Air Pollution
- Waste Management
- Energy Systems and Technology



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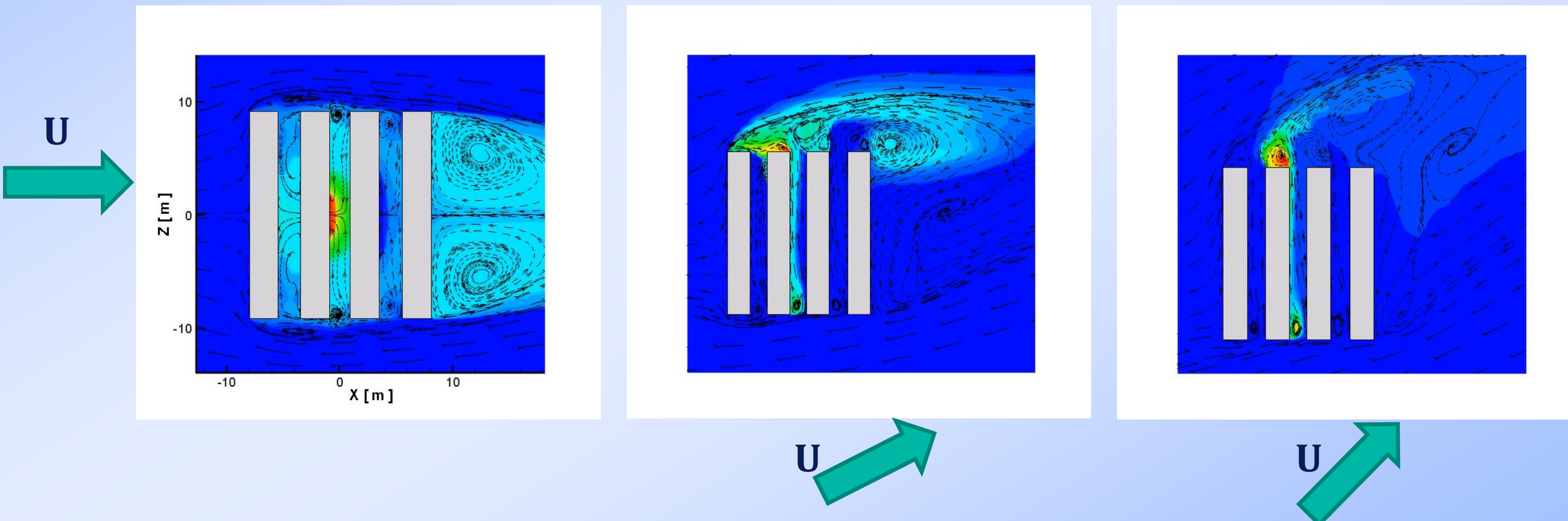
Example of dispersion in streets

Flow and dispersion fields under the influence of 3D building geometry in an artificial series of streets (the PICADA project Guerville experiment) - Bird's eye view



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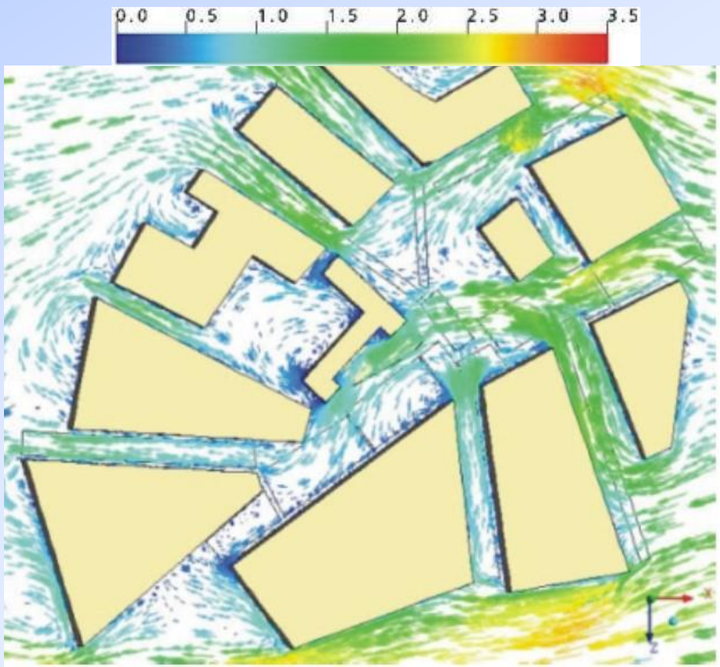
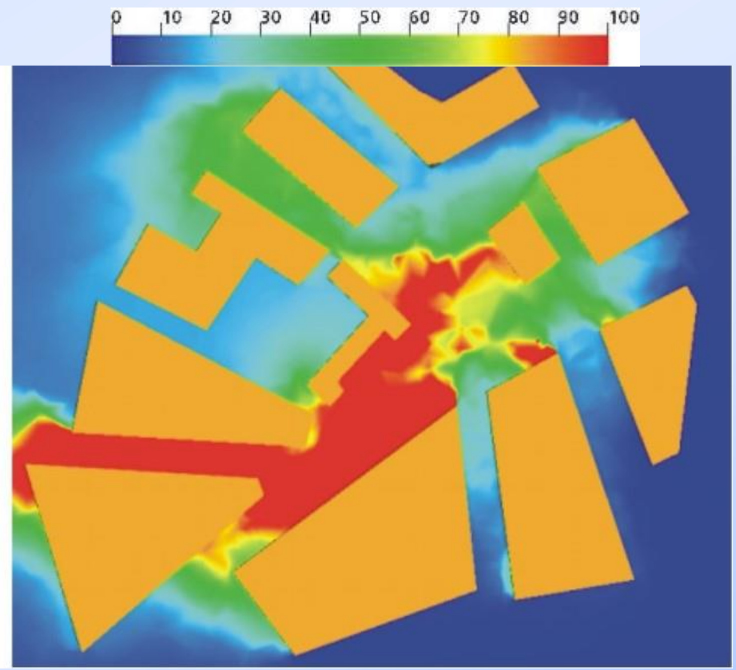
Example of numerically calculated flow and dispersion fields in Central London

Wind speed (m s^{-1})



NO_x (μg m^{-3})



U (*WD* = *90°*)

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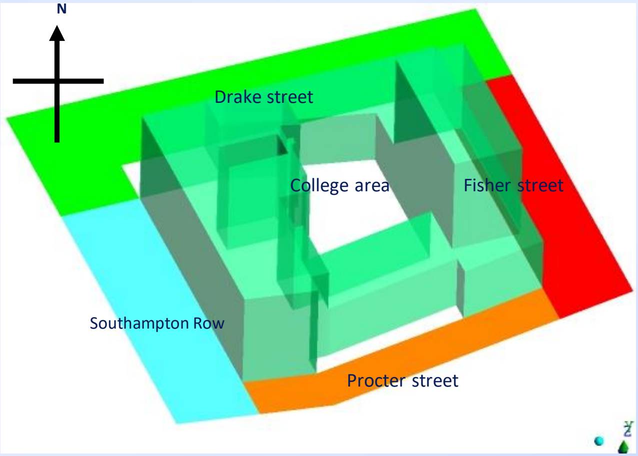

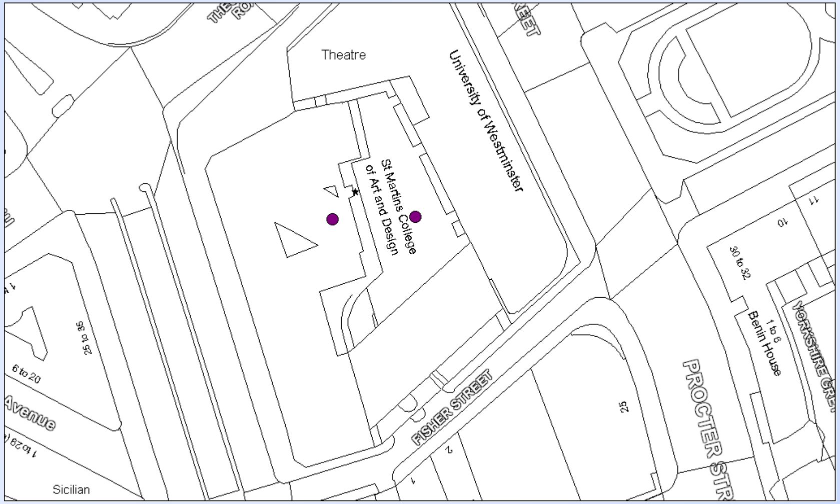

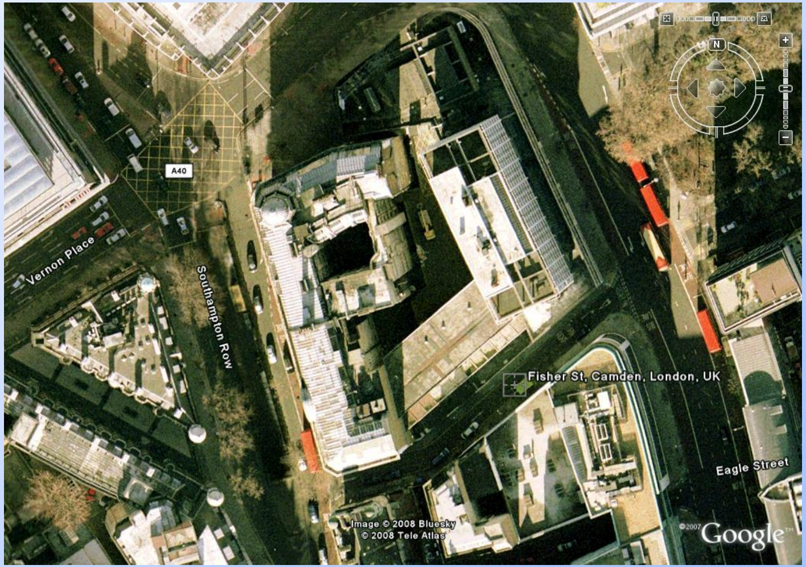

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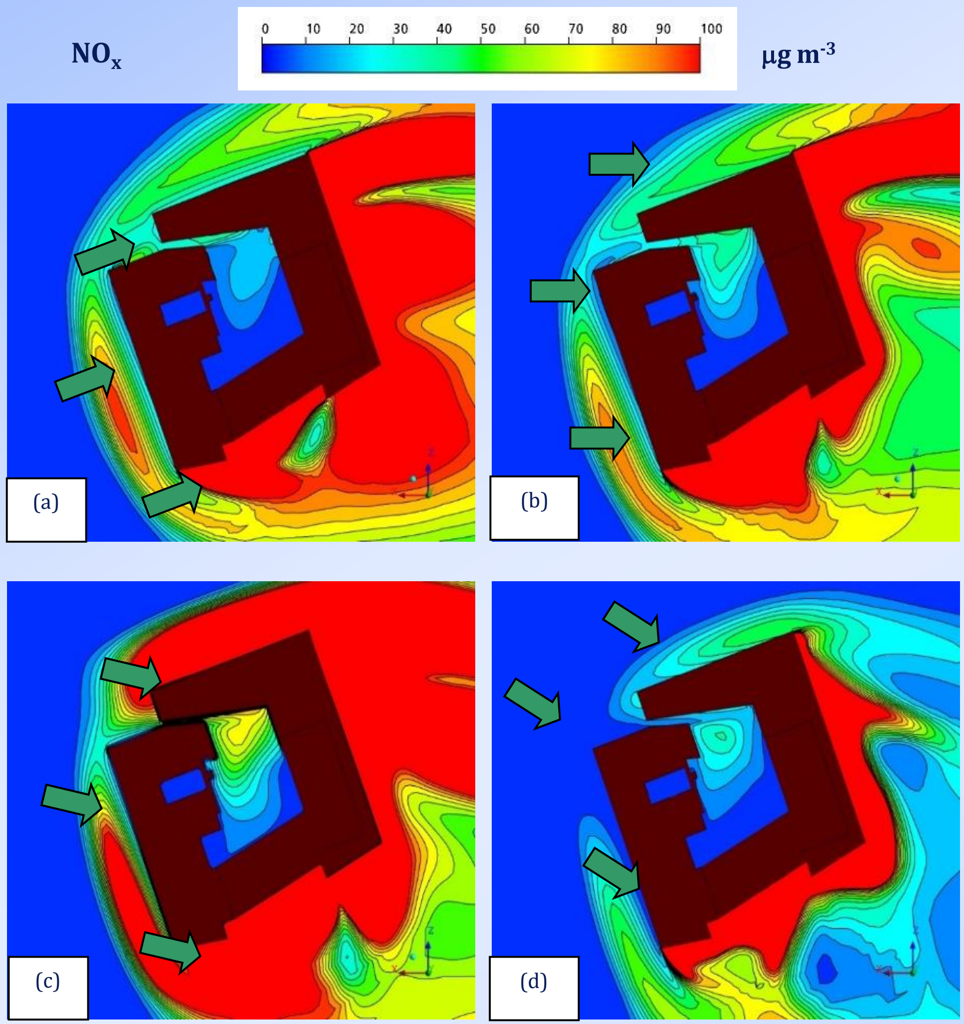

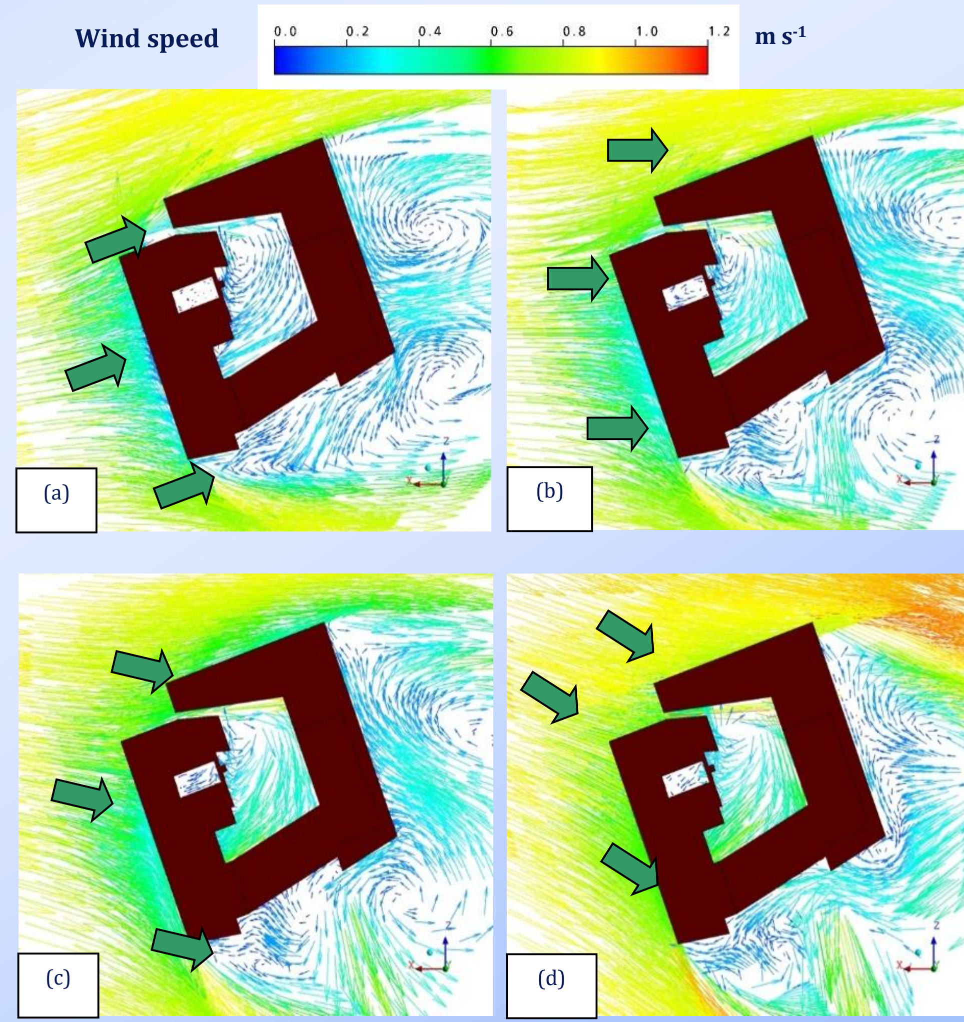

Other examples of real life application of CFD

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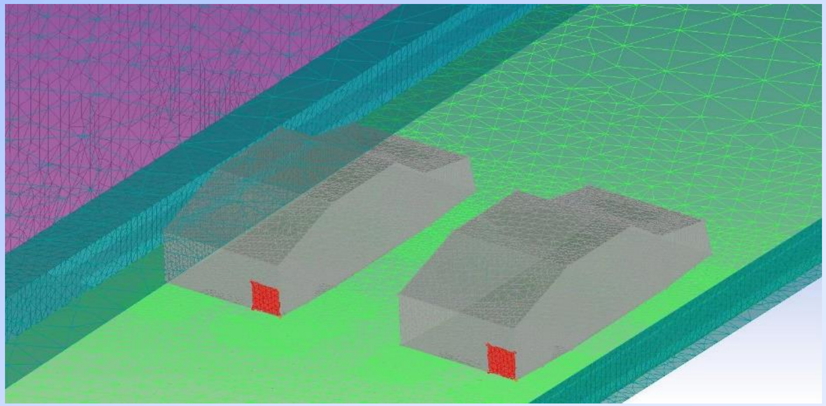
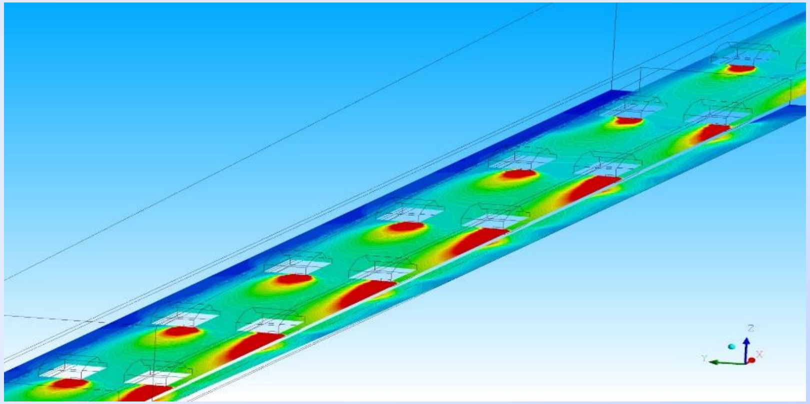
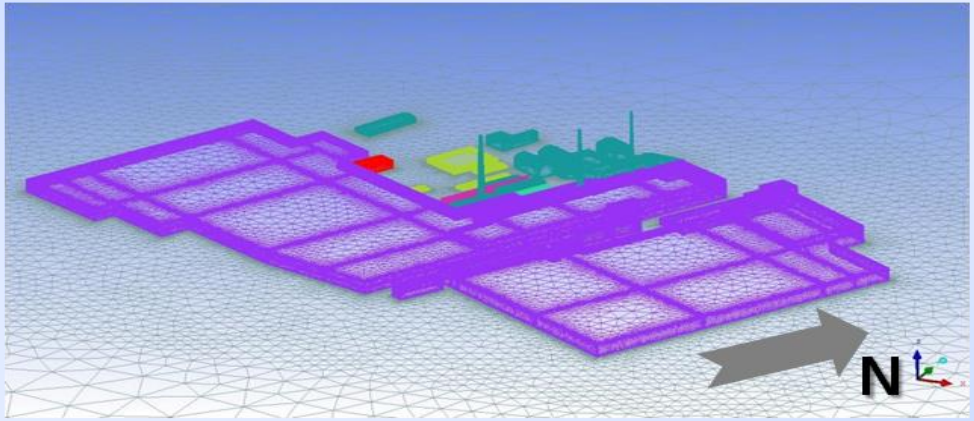
Leopold II road tunnel field trial, Brussels, Belgium

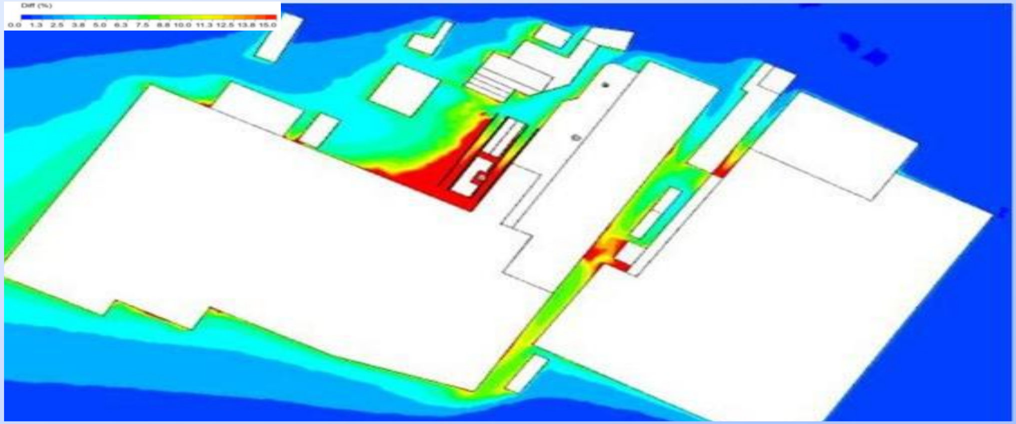


Moving mesh technique applied – impact of vehicles motion quantified



Industrial site application (Italcementi), Bergamo, Italy





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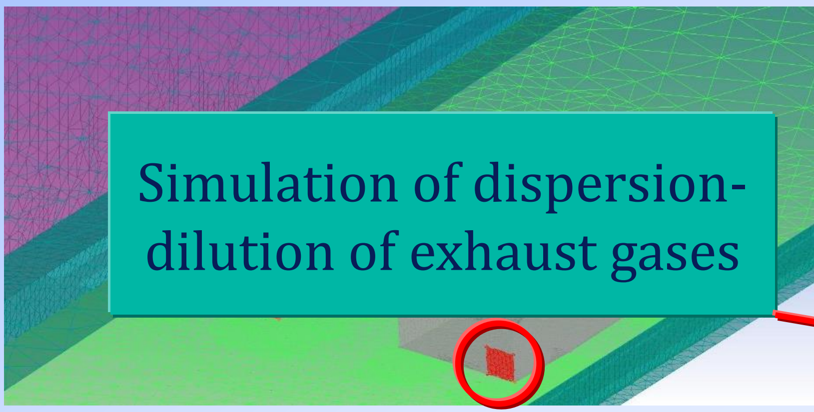

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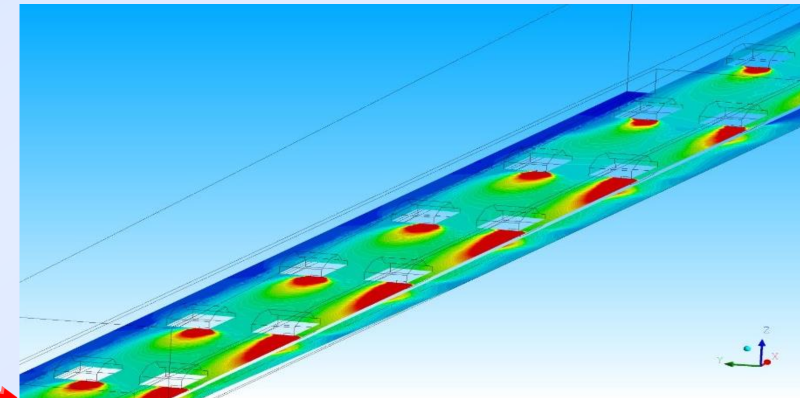

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