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A metamodelling implementation of a two-way coupled mesoscale-microscale flow model for urban area simulations

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Outline

- Objective
- MEMO/MIMO
- One-way coupling
- Two-way coupling: a new approach
- Application: the Athens case

Objective

- To develop a multiscale model system by implementing two-way coupling between a mesoscale and a microscale model.

- To study the effectiveness of the new approach on predicting wind circulation and TKE production over built-up areas.

MEMO Mesoscale Model (1/2)

- Eulerian, non-hydrostatic prognostic mesoscale model.
- Describes atmospheric transport phenomena in the local-to-regional scale.
- Describes the dynamics of the atmospheric boundary layer by solving the conservation equations for momentum, mass and scalar quantities as energy, water vapour and, optionally, turbulent kinetic energy.
- The governing equations are solved numerically on a staggered grid.
- To simplify the formulation of the boundary condition at the irregular lower boundary terrain following coordinates are used instead of Cartesian coordinates.

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MEMO Mesoscale Model (2/2)

- Initialization of the model is performed using diagnostic methods: A mass-consistent initial wind field is formulated using an objective analysis model; scalar fields are initialized using appropriate interpolating techniques
- An one-dimensional heat conduction equation for the soil is also solved, in order to calculate the soil temperature and the heat flux into the soil.
- Capable of performing one-way nesting with a suitable formulation of the lateral boundary conditions for the fine grid.
- Input requirements : surface observations and sounding measurements (vertical profiles) for wind and temperature

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MEMO: History of applications

- Thessaloniki 1991 Measurement Campaign
- APSIS, The Athenian Photochemical Smog - Intercomparison of Simulations (EUROTRAC, 1993)
- NAIAS, New Airport Impact Assessment Study (Greek Ministry of the Environment, 1995)
- Auto-Oil Study (European Commission, 1996)
- “Athens 2004” Air Quality Study (Athens 2004 Bit Committee, 1997)
- Transboundary Air Pollution
- Recent projects: INFOS, CityDelta, MERLIN, ATREUS, TAGARADES episode
- ESCOMPTE Measurement Campaign
- Upper Rhine Valley, Heilbronn, Basel, Graz, Barcelona, Lisbon, Madrid, Milano, London, Cologne, Lyon, Hague
- Outside Europe: Mexico, Colombia, Los Angeles, Tokyo

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MEMO: Recent and ongoing improvements

- An improved representation of the surface heat and moisture fluxes between the soil and the surface layer was introduced using a layered hydraulic and thermal soil model.
- Up-to-date land use and soil classification data are utilised in the hydraulic parameterisation of the soil model.
- An “online” coupling of the MEMO model with the photochemical dispersion model MARS-aero is being implemented, the latter incorporating an aerosol module being able to calculate secondary inorganic and organic species (ongoing)

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The microscale model MIMO

- MIMO: Reynolds Averaged Navier Stokes (RANS) CFD model.
- Solves the Reynolds averaged conservation equations for mass, momentum and energy.
- Additional transport equations for humidity, liquid water content and passive pollutants can be solved.
- Reynolds stresses and turbulent fluxes of scalar quantities can be calculated by several linear and nonlinear turbulence models.
- A staggered grid arrangement is used and a coordinate transformation is applied to allow non-equidistant mesh size in all three dimensions in order to achieve a high resolution near the ground and near obstacles.
- Heat transfer which results into buoyant effects on the flow field also approximated.

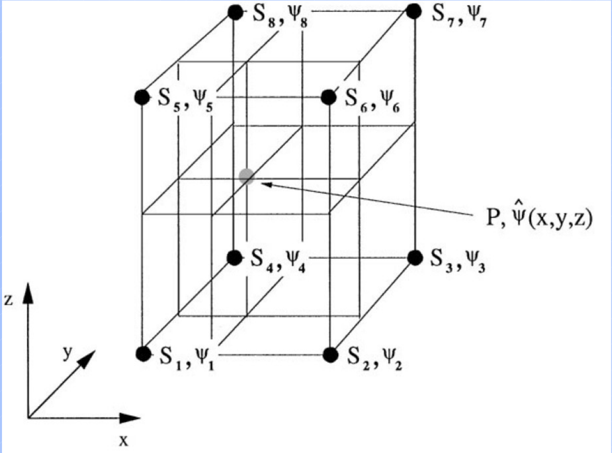
One-way MEMO-MIMO coupling

- Simulates the effect of the mesoscale flow on the microscale domain.
- Computational domain scales:
  - mesoscale domain: ~100-300km
  - microscale domain: <500m
- Characteristic timesteps:
  - mesoscale: 10s
  - microscale: ~1ms
- The two models are running semi-independently (“off-line coupling”)
- Any microscale domain can be arbitrarily nested.

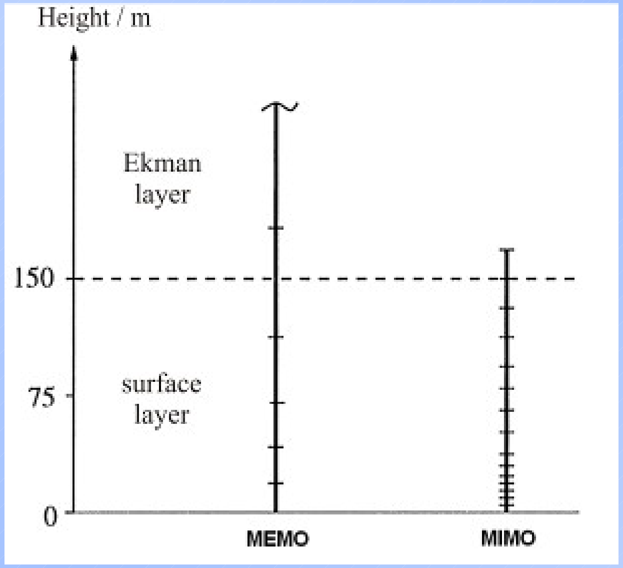
(Kunz *et al*, 2000)

One-way MEMO-MIMO coupling

- 3D interpolation scheme for calculating microscale BCs from mesoscale fields



$$\hat{\psi} = \frac{1}{\sum_{i=1}^{8} V_i} \sum_{i=1}^{8} [V_i \cdot \psi_i]$$



- Adjustment of the interpolated values within the surface layer.

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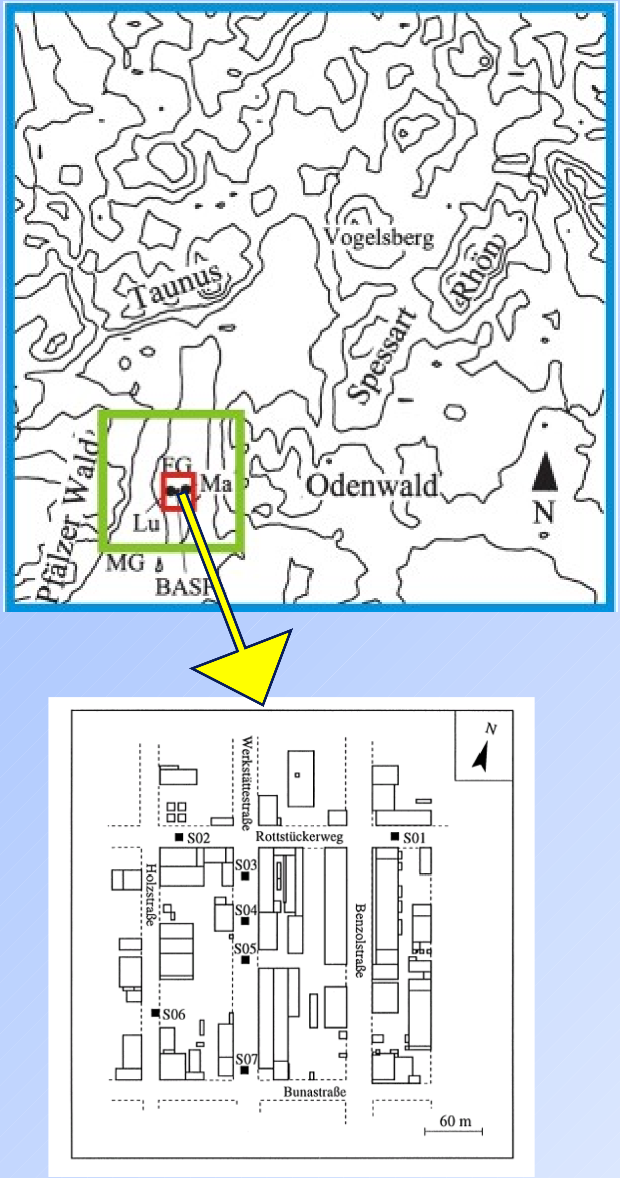
One-way MEMO-MIMO coupling

Application: calculation of wind flow over the BASF industrial area in southeastern Germany

(Kunz *et al*, 2000)



- MEMO: triply nested domain, 24h simulation period.
- MIMO: single domain with dimensions 360× 400 m, four typical periods of day: 09:00, 12:00, 15:00, 21:00.

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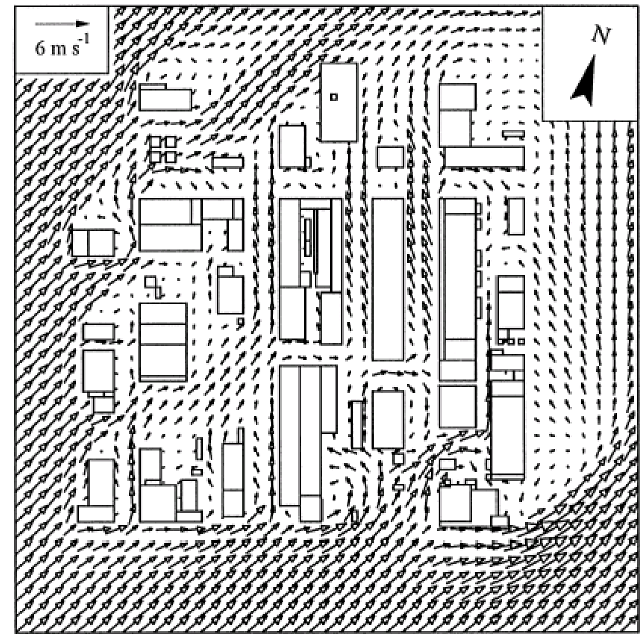
One-way MEMO-MIMO coupling

Application: calculation of wind flow over the BASF industrial area in southeastern Germany

- Predicted microscale wind velocities in good agreement with measurements.
- Slight overestimation may be due to partial coverage of the industrial area causing underestimation of drag effects.



Comparison between measurements and numerical simulation

	Measurements		Simulation	
Station	$\bar{u}$/m s^{-1}	φ/°	$\bar{u}$/m s^{-1}	φ/°
S01	0.93	248–275	1.29	254–268
S02	1.03	256–284	1.28	234–258
S03	1.29	140–178	1.79	151–169
S04	1.28	130–175	1.74	148–169
S05	1.33	165–250	1.70	160–196
S06	1.70	175–202	2.07	186–197
S07	1.72	150–250	2.36	205–234

One-way MEMO-MIMO coupling: successes

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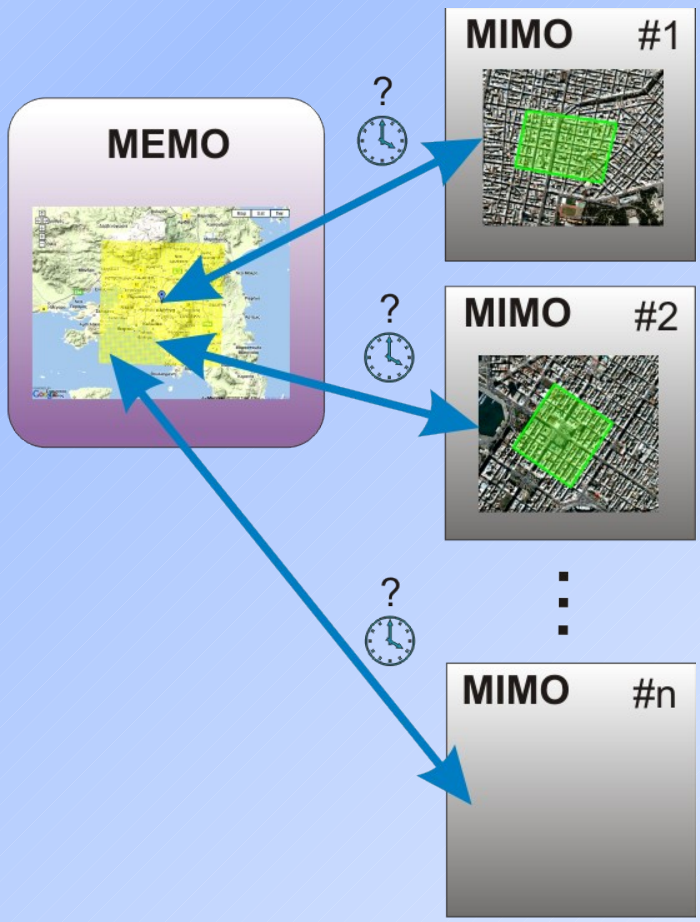
- A reasonably accurate prediction of the microscale flow.
- Predictions of statistically important “typical” microscale flow patterns (e.g. for specific hours of the day)
- Can be combined with a coupled mesoscale-street-scale **dispersion** model for predicting 3D dispersion of pollutants within streets & buildings.

One-way MEMO-MIMO coupling: shortcomings

- Huge spatial & temporal **scale mismatches** prohibit on-line coupling (MEMO would have to slow to a crawl).
- 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 100s of urban cells)



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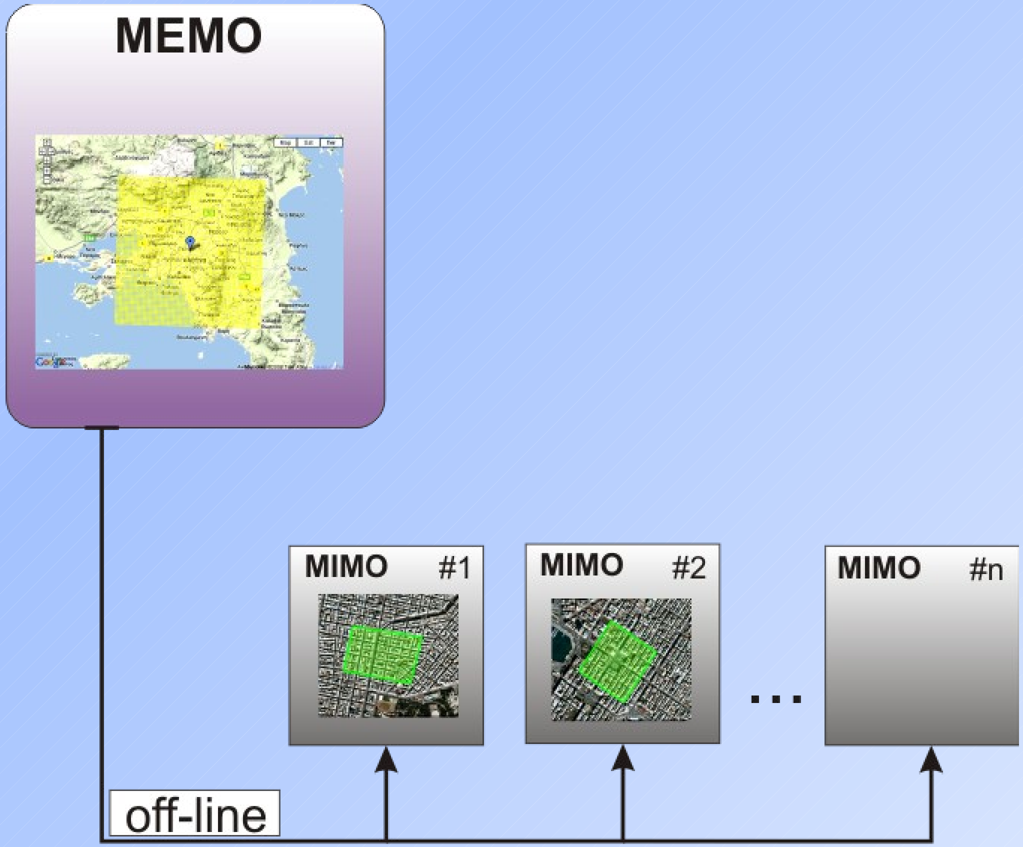
Two-way MEMO-MIMO coupling: additional requirements

1. The effect of the microscale domain on the mesoscale flow should be also adequately simulated.
2. Multiple microscale domains should be simulated, in order to better represent the entire urban area.
3. A methodology should be devised, to enable two-way coupling over largely differing scales.

Two-way MEMO-MIMO coupling using an interpolating metamodel

Three-step approach:

1st step: BCs calculated from an initial MEMO run are used for multiple MIMO cases off-line.



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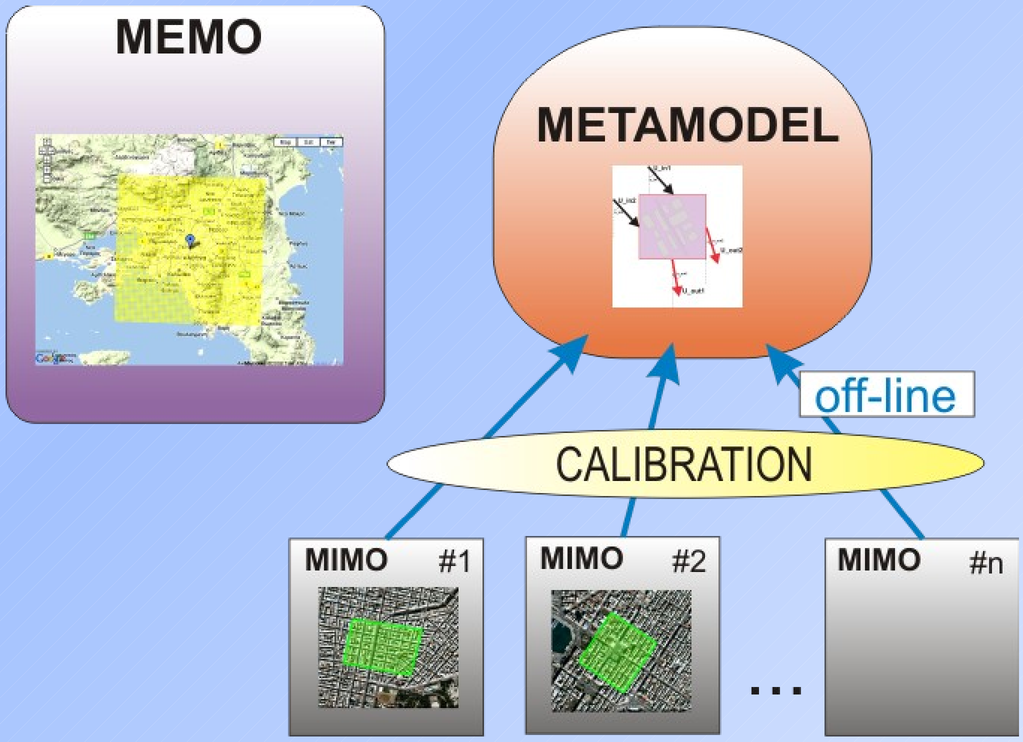
Two-way MEMO-MIMO coupling using an interpolating metamodel

Three-step approach:

2nd step: the response of each microscale domain is used as calibration input for an interpolating metamodel.

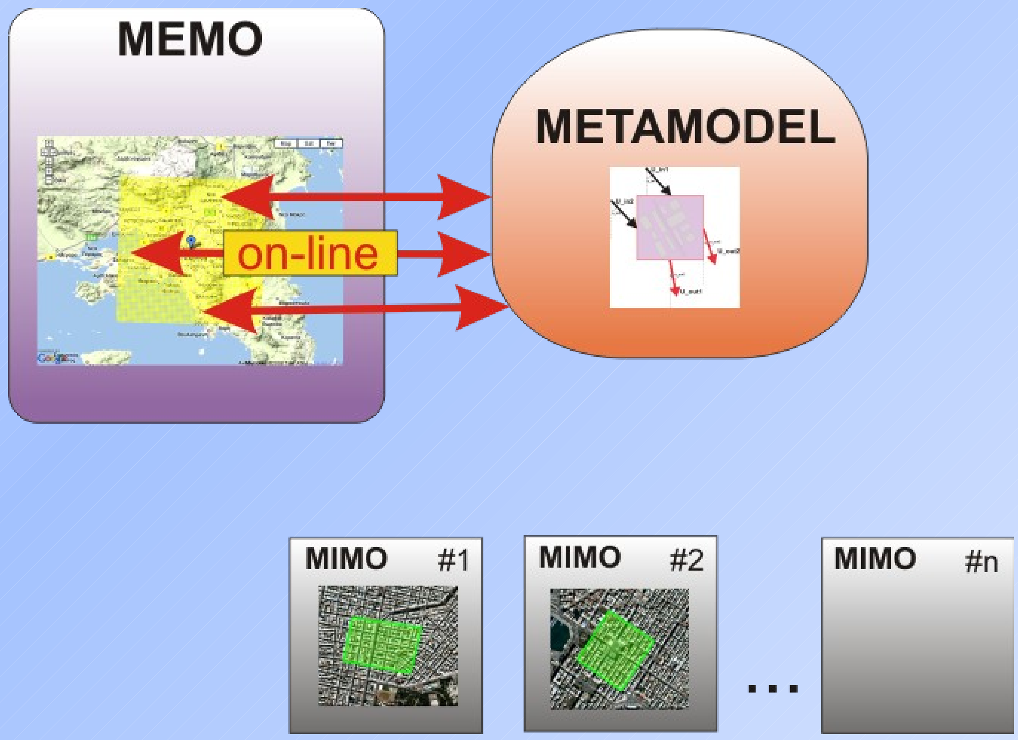


(Piñeros Garcet *et al*, 2006)

Two-way MEMO-MIMO coupling using an interpolating metamodel

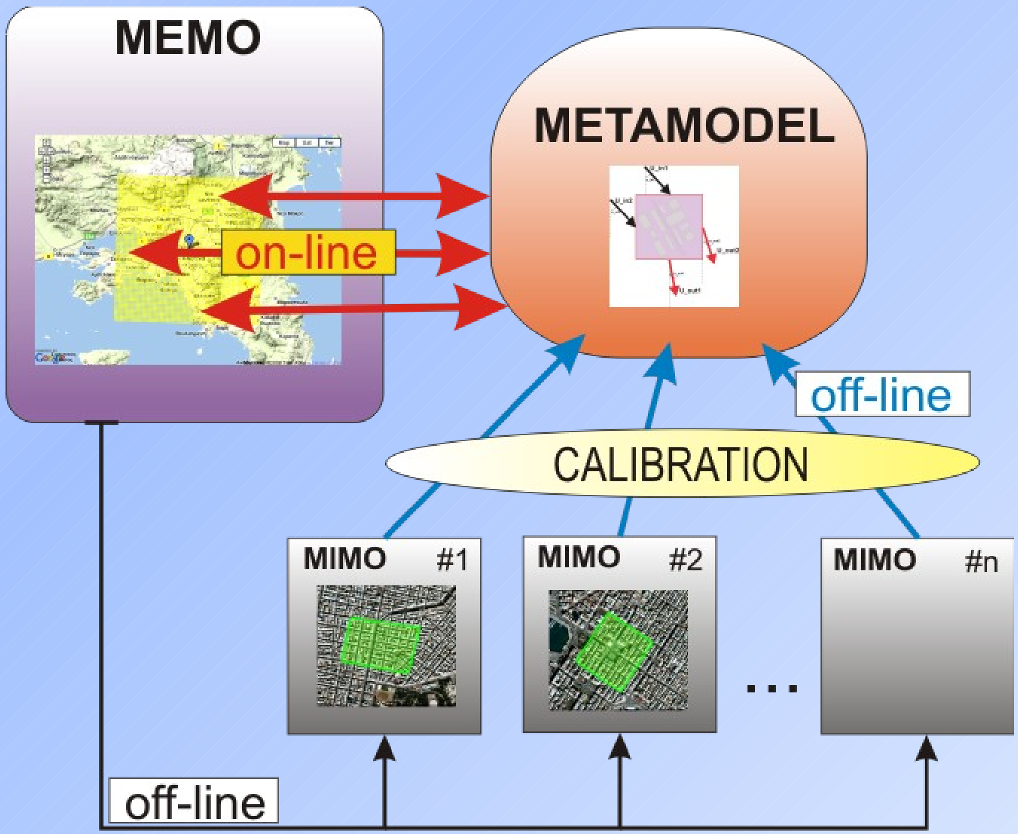
Three-step approach:

3rd step: the calibrated metamodel is fast enough to be used in on-line coupling with MEMO.



Two-way MEMO-MIMO coupling using an interpolating metamodel

- It is possible to iteratively repeat the three steps in order to more accurately simulate the microscale effect on the mesoscale simulation.
- Experience shows that gains from >2 iterations are negligible.



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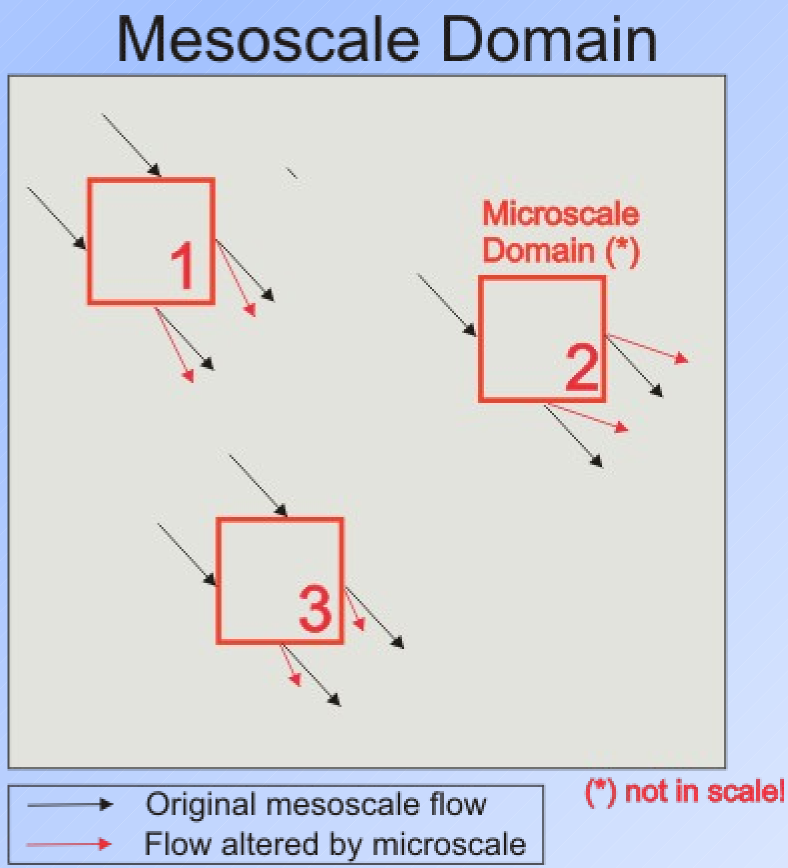
Two-way MEMO-MIMO coupling: basic features

- Incorporation of multiple microscale domains
- The effect of each domain is independent from the others.



Two-way MEMO-MIMO coupling: spatial sampling/classification

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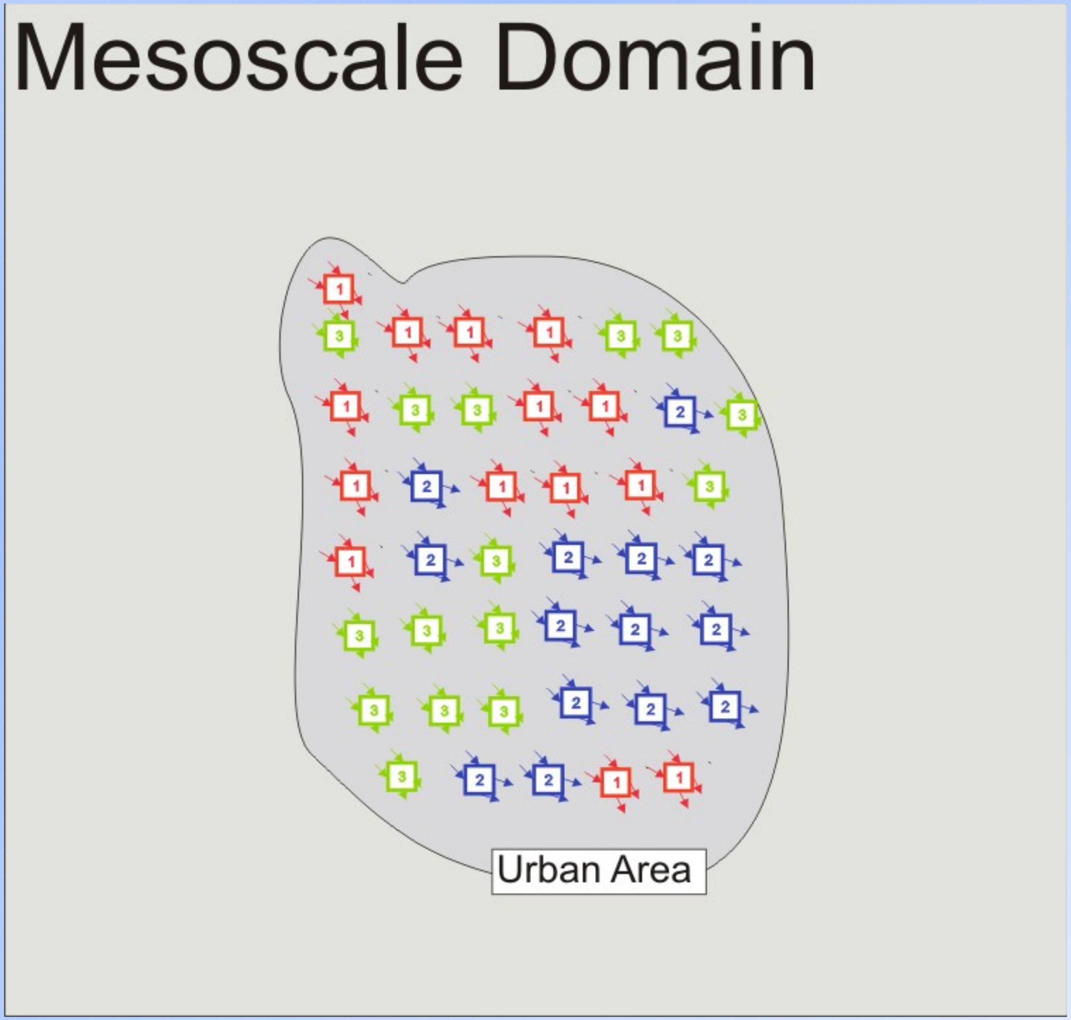
- Each mesoscale cell is classified according to average building orientation and height.

- The dynamical “microscale effect” is parameterised for each urban cell using an interpolating metamodel.



Two-way MEMO-MIMO coupling: temporal sampling

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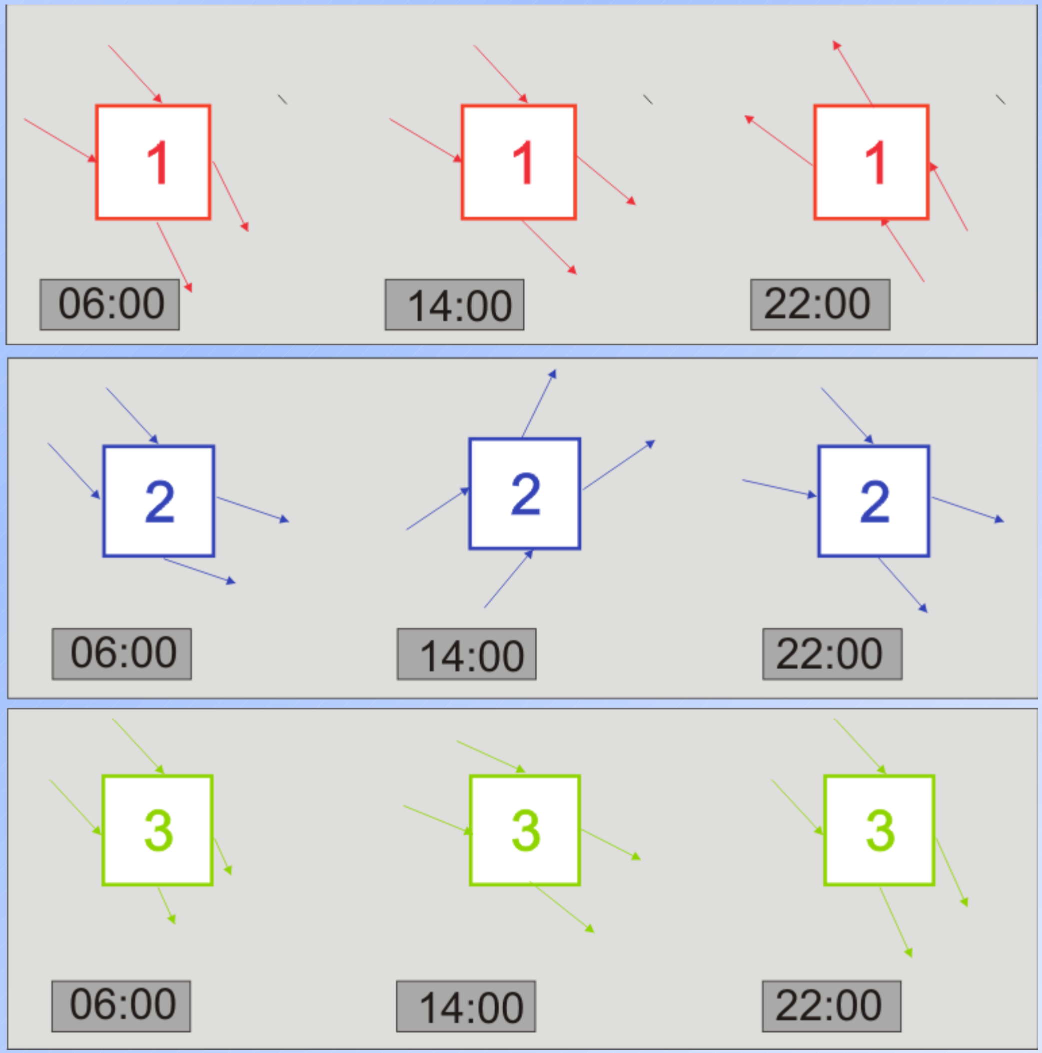
- Three or four periods for each day
- Each period should correspond to a typical wind direction



Two-way MEMO-MIMO coupling: parameterising the microscale response

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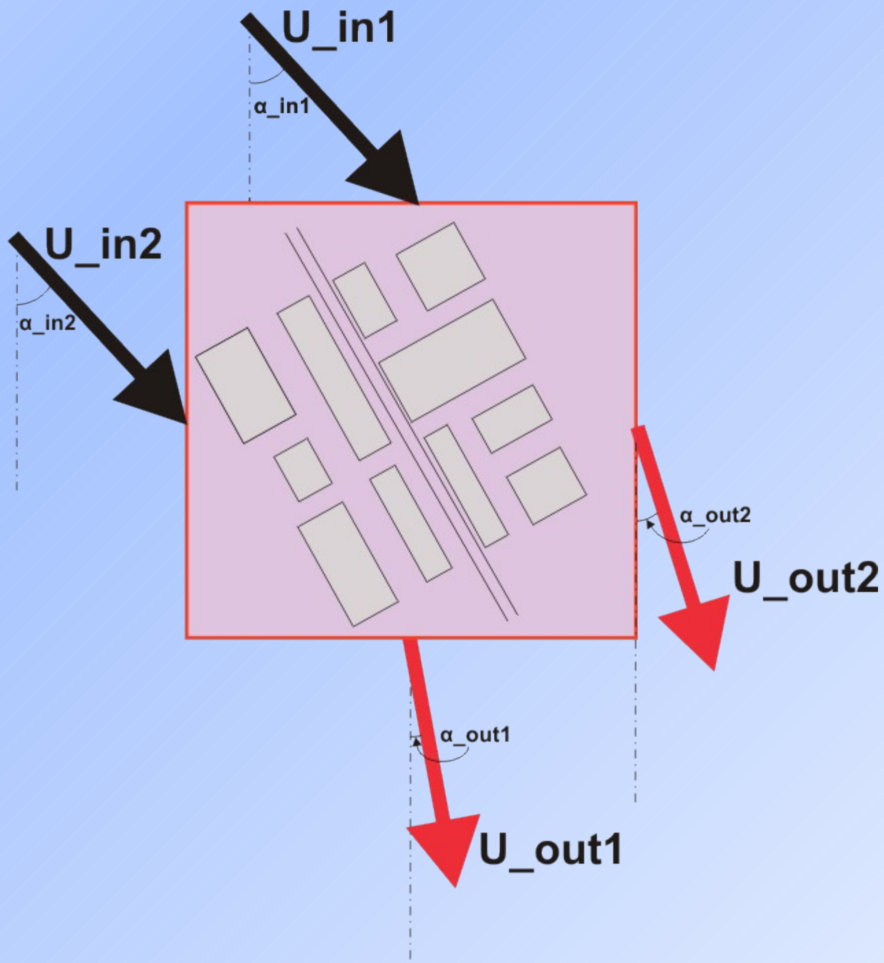
- From MIMO runs: determine the functions **U_out2** and **U_out1** for various inflow conditions, street orientations and building heights.

Microscale Domain



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Two-way MEMO-MIMO coupling: parameterising the microscale response

- General interpolation scheme:

$$\psi(z) = \frac{\sum_k R_k(z)\,\psi_k(z)}{\sum_k R_k(z)}$$

- Area-averaged attenuation profiles (velocity):

$$\psi(z)=u_{\mathrm{out}}(z)/u_{\mathrm{in}}(z)$$

$$\psi^k(z)=u^k_{\mathrm{out}}(z)/u^k_{\mathrm{in}}(z)$$

$$R_k(z) = \left[u_{\mathrm{in}}(z) - u^k_{\mathrm{in}}(z)\right]^n$$

- Deflection profiles (direction):

$$\psi(z) = \left[\hat{a}_{out} - \hat{a}_{in}\right]^n$$

$$\psi_k(z) = \left[\hat{a}_{out,k} - \hat{a}_{in,k}\right]^n$$

$$R_k(z) = \left[(\hat{a}_{in}, \hat{a}_{in,k})^2 w_1 + (u_{in} - u_{in,k})^2 w_2\right]^n$$

Two-way MEMO-MIMO coupling: parameterising the microscale response

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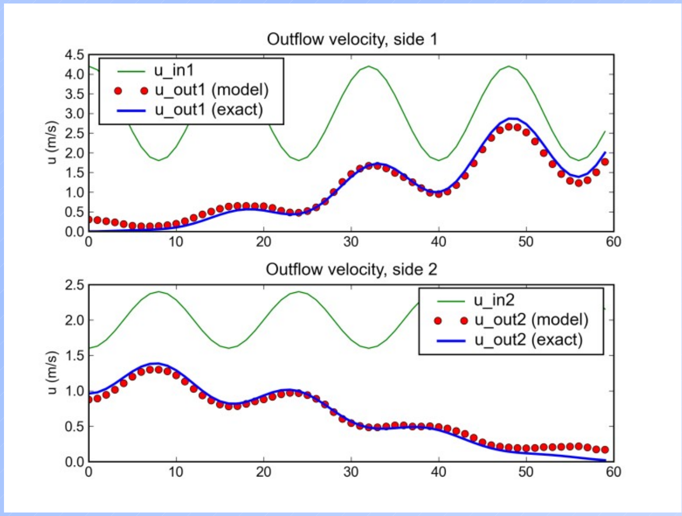
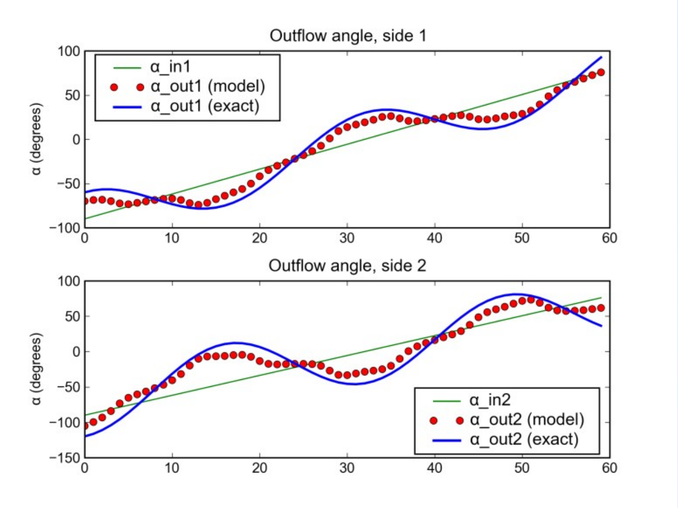
- N=8 synthetic calibration cases, n=60 synthetic inflow test cases.
- Interpolation error increases with increasing distance from the calibration conditions.





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Two-way MEMO-MIMO coupling: use of Newtonian relaxation

- The effect of the microscale domain is introduced in the mesoscale using Newtonian relaxation (“observational” nudging).

(Stauffer *et al*, 1990)

- Nudging is performed on temperature, momentum and TKE on the 4 lower mesoscale layers.

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Athens area: test case

Mesoscale case

- Period: 8-12 May 2002
- Spatial extent: The entire Attica peninsula
- Nesting: Doubly nested grid

Microscale (calibration) cases

- Period: 4 representative hourly periods during the POI (8-12/05/2002)
- Spatial extent: 2 downtown areas in Athens
- Grid setup: Structured grids (~5×10^6 cells)

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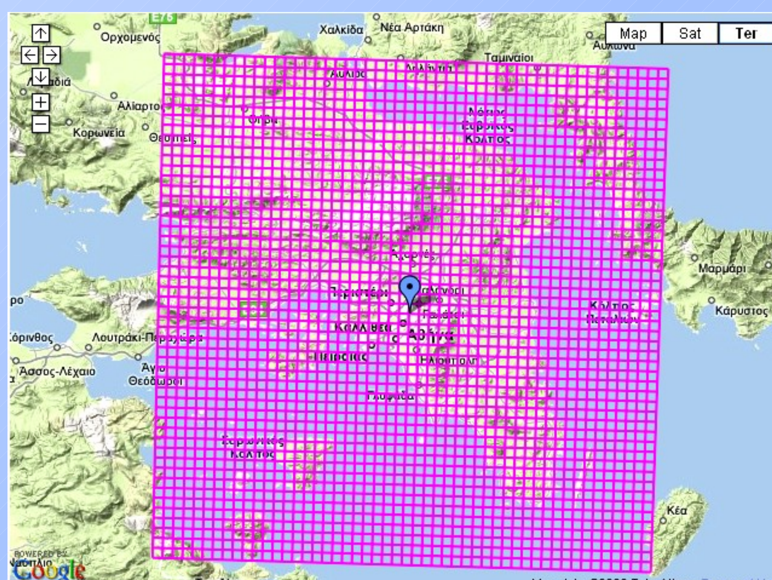
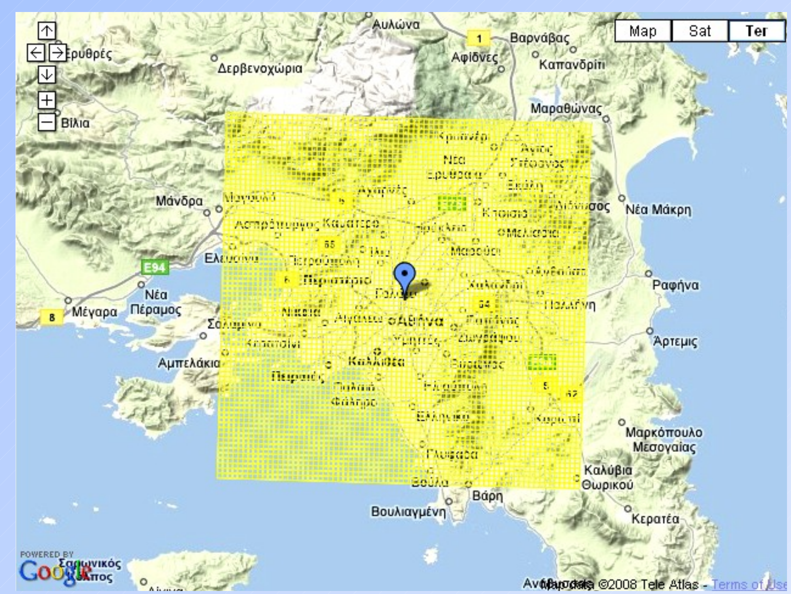
Athens area: mesoscale grid

Grid	No of cells	Cell dimensions	Total grid extent	Initial/Boundary Conditions
Coarse	50× 50× 25	2× 2 km^2	100× 100 km^2	From 1 sounding location (via University of Wyoming)
Fine	72× 72× 25	500× 500 m^2	36× 36 km^2	Obtained from the coarse grid





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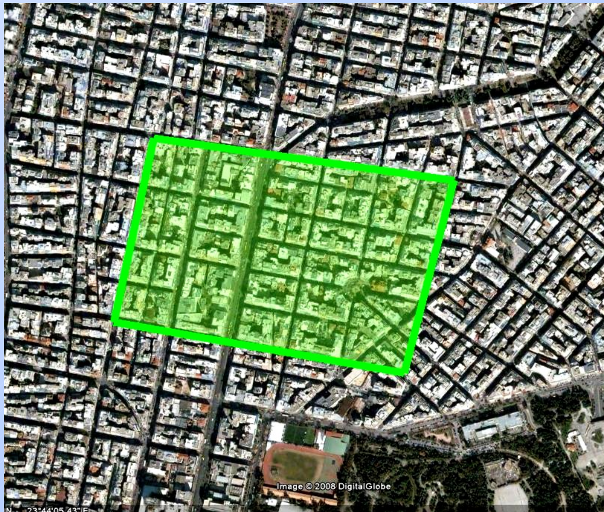
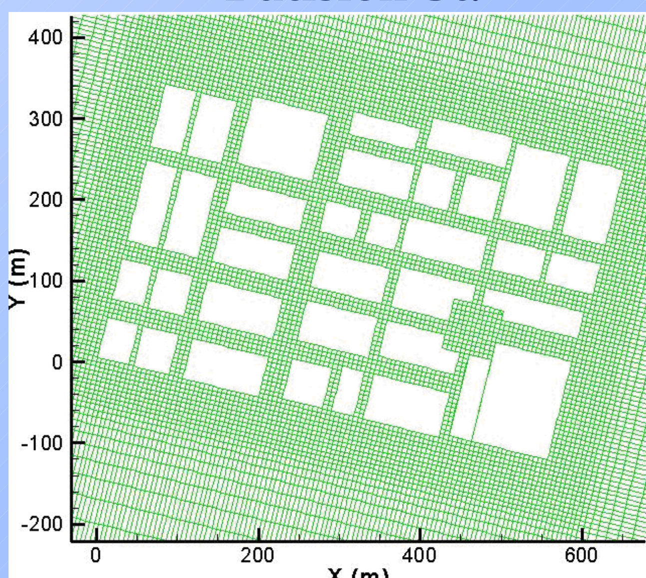
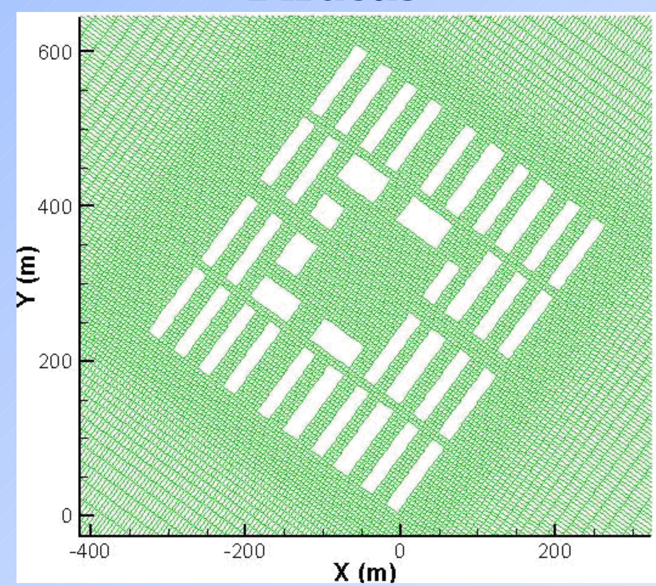
Athens area: microscale grids



Patision St.

Piraeus





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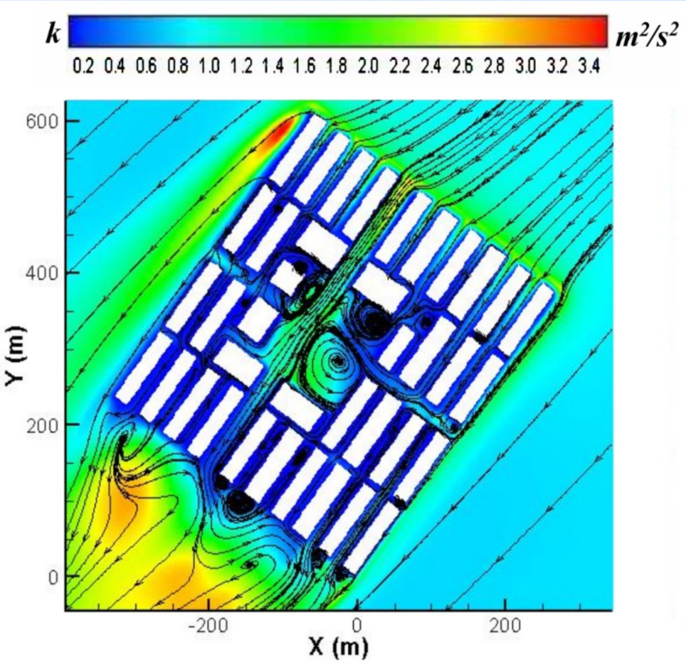
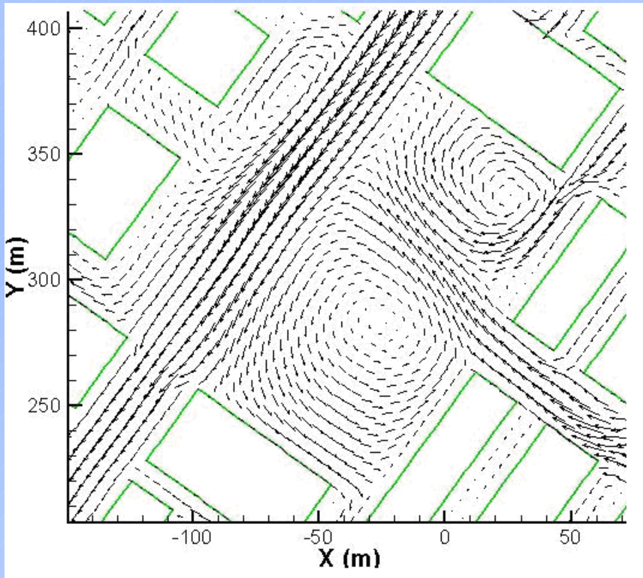
Athens area: microscale case setup

- Two representative areas of linear dimension ~500m
- Four simulated periods
  1. 08/05/2002:11:00 NE winds, very unstable
  2. 09/05/2002:12:00 SE winds, very unstable
  3. 11/05/2002:09:00 WNW winds, unstable
  4. 11/05/2002:16:00 SW wind, unstable

Athens area: microscale simulation Piraeus domain





- Overall deceleration of the flow within the built-up area.
- TKE levels are reduced within narrow street canyons.
- A slight increase of TKE is observed over the large open area at the centre of the domain.

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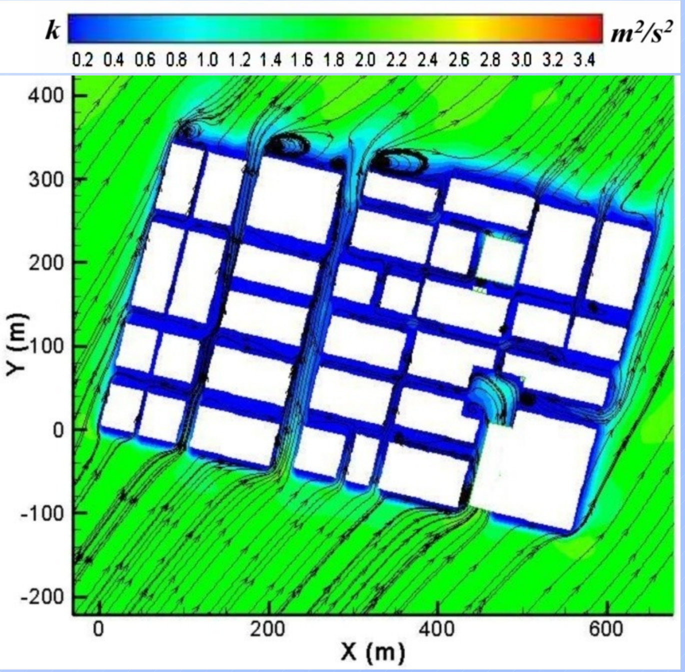
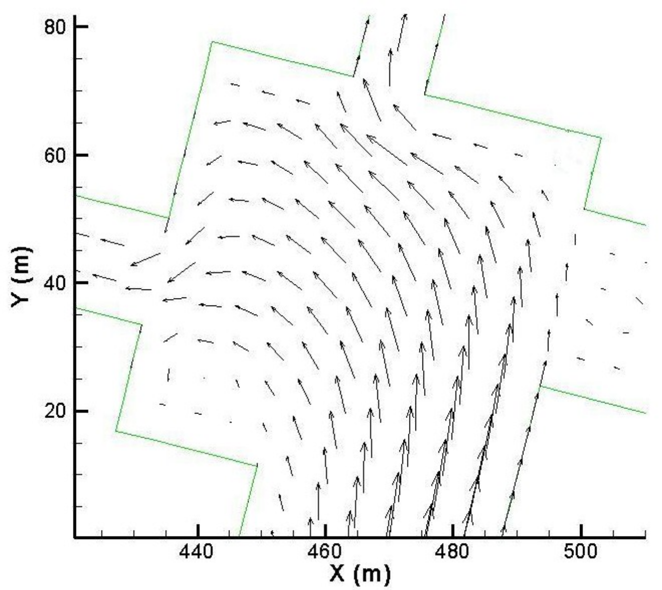
Athens area: microscale simulation Patision domain





- Overall deceleration of the flow within the built-up area.
- TKE levels are reduced within narrow street canyons.

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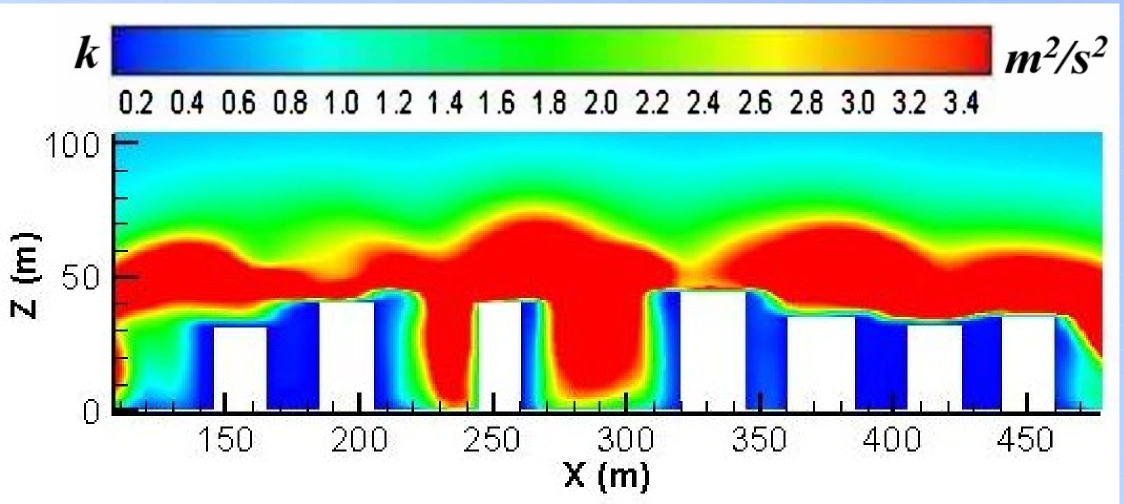
Athens area: microscale simulation



- TKE production above roof level is increased.
- The effect of urban canopy in TKE production is confined within a layer of thickness ~1.5 times the average building height.
- Previous numerical and physical simulations indicated enhanced production up to ~2 times the building height (Davidson *et al*, 1996; Hanna *et al*, 2002; Barmpas *et al*, 2005; Milliez and Carrisimo, 2007; Santiago *et al*, 2007).

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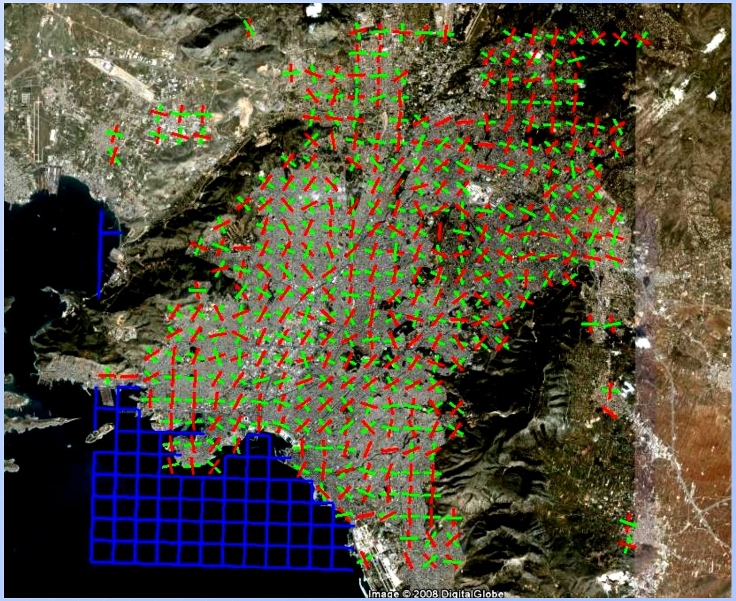
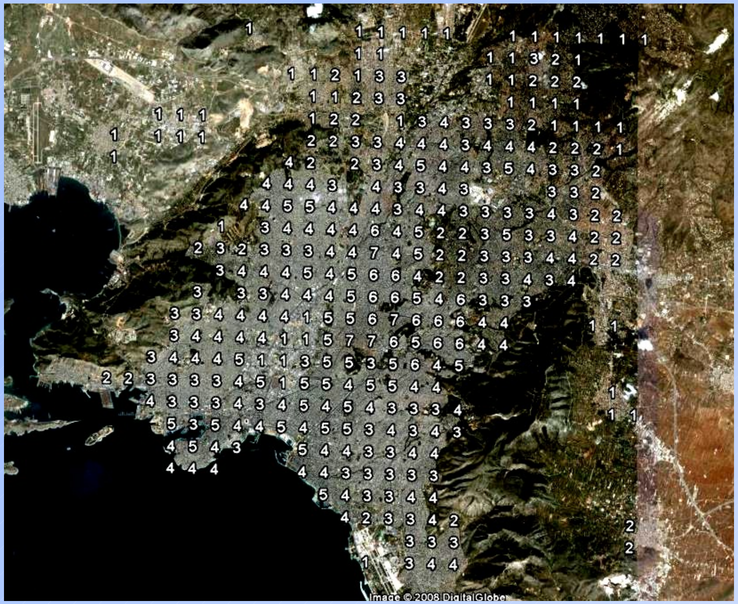
Athens area: classification of urban cells





- “Urban” mesoscale cells are selected based on building density.
- A prevailing <u>street orientation</u> is determined for each cell (left).
- Average <u>number of building stories</u> (floors) is obtained from GIS maps (right).

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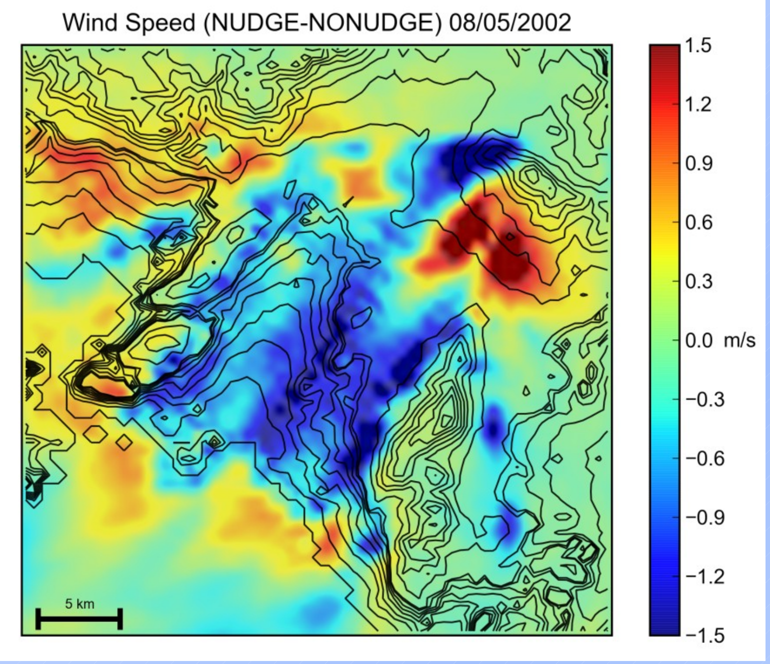
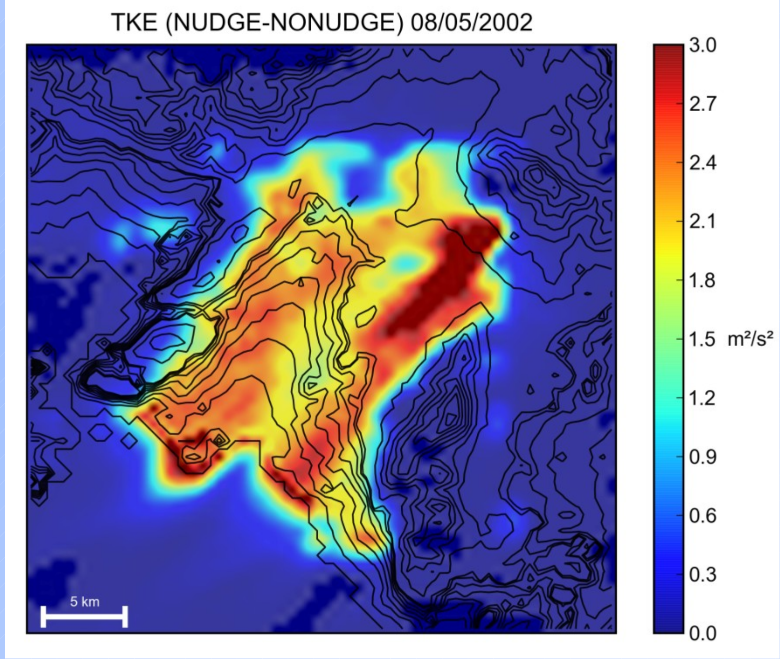
Athens area: results from the coupled system





- The velocity difference map for the first layer (0-20m) (left) implies a notable reduction of about 0.5-1.0 ms^{-1} over the urban area.
- A significant increase in TKE production is evident over the 2^{nd} layer (20-40m).

Athens area: results from the coupled system

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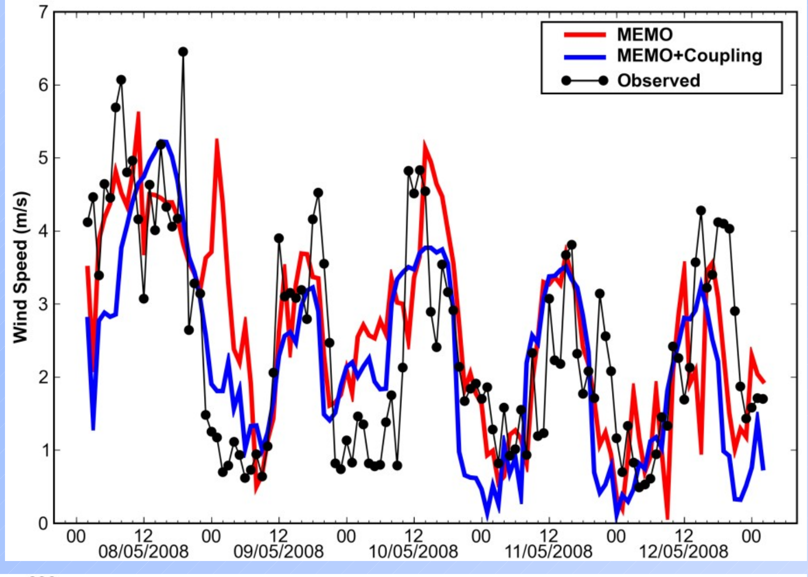
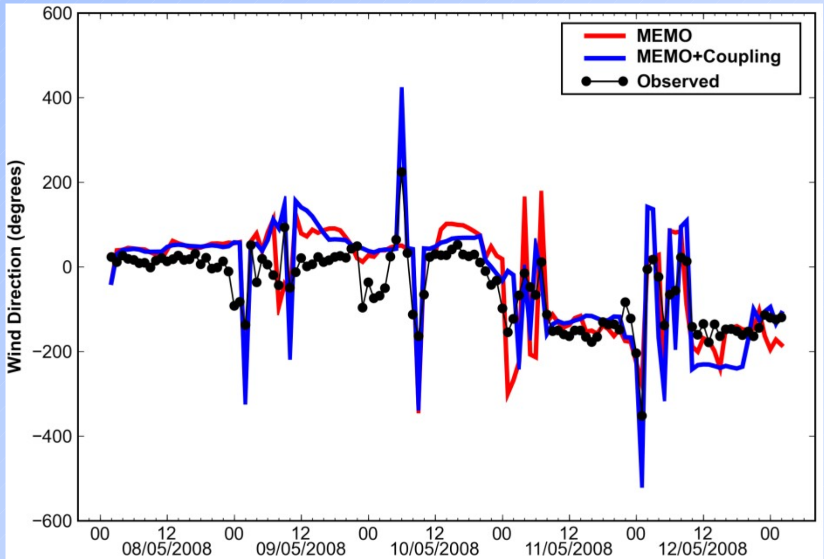
Measurement Station at
<u>Patision St.</u>

- Introduction of coupling systematically reduces calculated velocities over the entire simulation period.
- Timeseries of wind direction calculated with and without coupling do not reveal significant differences.





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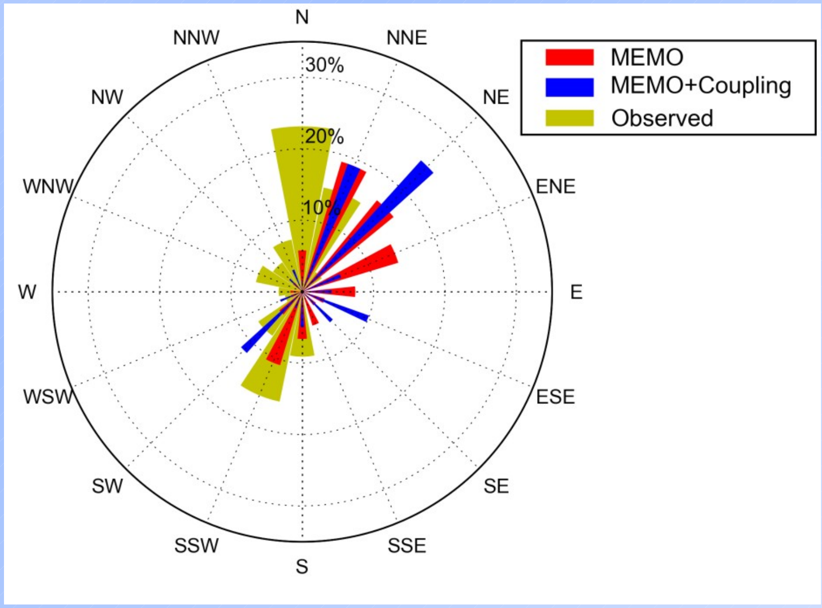
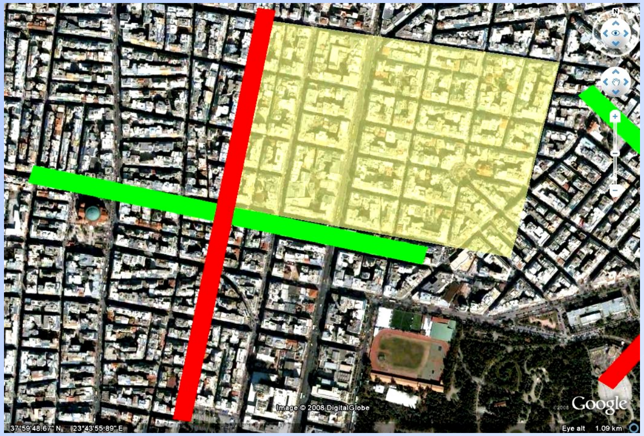
Athens area: results from the coupled system

Measurement Station at <u>Patision St.</u>



•Wind directions calculated with coupling show a tendency to align with prevailing street direction.

•Measurements underestimate local streaming effects since the measuring station operates 4 m above roof level.



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Future work

- Investigate alternative metamodelling formulations.
- Application to urban areas of various geometrical characteristics (building density/ height, aspect ratio of street canyons).
- Comparison with wind-tunnel measurements.
- Validation through comparison with combined roof- and street-level measurements from urban stations.

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References

Barmpas P., B. Leitl, N. Mousssiopoulos and M. Schatzmann (2005) Physical modelling of flow and dispersion in and around an idealized street canyon – replicating the PICADA field experiment in a boundary layer wind tunnel, *Proceedings of the 5th International Conference on Urban Air Quality*, Valencia, Spain 29-31 March.

Clapp R. G. and Hornberger (1978) Empirical equations for some soil hydraulic properties, *Water Resources Research*, **14**, 601-604.

Davidson M.J., W.H. Snyder, R.E. Lawson Jr and J.C.R. Hunt (1996) Wind tunnel simulations of plume dispersion through groups of obstacles, *Atmospheric Environment*, **30**, 3715-3731.

Grimmond C.S.B. and T.R. Oke (1999) Heat storage in urban areas: local-scale observations and evaluation of a simple model, *Journal of Applied Meteorology*, **38**, 922-940.

Hanna S.R., S. Tehranian, B. Carrisimo, R.W. Macdonald and R. Lohner (2002) Comparisons of model simulations with observations of mean flow and turbulence within simple obstacle arrays, *Atmospheric Environment*, **36**, 5067–5079.

Jones W. and B. Launder (1973) The calculation of low-Reynolds-number phenomena with a two equation model of turbulence, *International Journal of Heat and Mass Transfer*, **16**, 1119-1130.

Khatib I. (1998) Verfahren zur Verknüpfung mesoskaliger und mikroskaligen Modellen der atmosphärischen Grenzschicht, *Fortschritt-Berichte der VDI-Zeitschriften*, **205** (15), p. 115.

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References

Kunz R., I. Khatib and N. Moussiopoulos (2000) Coupling of mesoscale and microscale models – an approach to simulate scale interaction, *Environmental Modelling & Software*, **15**, 597-602.

Milliez M. and B. Carrisimo (2007) Numerical simulations of pollutant dispersion in an idealized urban area, for different meteorological conditions, *Boundary-Layer Meteorology*, **122**, 321–342.

Piñeros Garcet J.D., A. Ordoñez, J. Roosen and M. Vanclooster (2006) Metamodelling: Theory, concepts and application to nitrate leaching modelling, *Ecological Modelling*, **193**, 629-644.

Sailor D. (1993) Role of surface characteristics in urban meteorology and air quality, Ph.D. dissertation, University of California, Berkeley, 174 pp.

Santiago J.L., A. Martilli and F. Martin (2007) CFD simulation of airflow over a regular array of cubes. Part I: 3-D simulation of the flow and validation with wind tunnel data, *Boundary-Layer Meteorology*, **122**, 609-634.

Stauffer D.R. and N.L. Seaman (1990) Use of Four-Dimensional Data Assimilation in a Limited-Area Mesoscale Model. Part I: Experiments with Synoptic-Scale Data, *Monthly Weather Review*, **118**, 1250-1277.

Taha H., H. Akbari and D. Sailor (1992) Causes and effects of heat islands: The sensitivity of urban microclimates to surface parameters and anthropogenic heat, Lawrence Berkeley National Laboratory Technical Report LBL-29864.