

Coupling of mesoscale and microscale models—an approach to simulate scale interaction

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Abstract

Atmospheric flow and pollutant dispersion over built-up areas are affected by phenomena occurring at different scales. Hence, scale interactions should also be considered in the mathematical modelling of atmospheric flow and pollutant dispersion. In this paper a method is presented to couple prognostic mesoscale and microscale flow models. Results from mesoscale simulations are used to generate the initial state and boundary conditions for microscale simulations. The method comprises a three-dimensional interpolation scheme and a vertical adjustment of the interpolated quantities in the surface layer based on similarity theory. The method is applied to couple the microscale model MIMO with the mesoscale model MEMO.

The coupled system MEMO–MIMO is applied to simulate the local scale flow for an industrial area in southwestern Germany. Model results are presented and compared with available measurements. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Local scale; Regional scale; Wind flow; Mathematical atmospheric models; Model hierarchy

Software availability

Program name: Prognostic mesoscale model MEMO,
prognostic microscale model MIMO

Developer: Institut für Technische Thermodynamik,
Universität Karlsruhe and Laboratory of Heat
Transfer and Environmental Engineering, Aris-
totle University Thessaloniki

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Years first available: 1989 (MEMO), 1994 (MIMO)

Hardware required: both models can be used on various
computer platforms ranging from a PC to a
supercomputer; for complex applications, how-
ever, at least an advanced workstation is rec-
ommended

Programming language: FORTRAN 90

Software required: any FORTRAN 90 compiler

Program size: depending on the application type, typi-
cal values are 50 MByte (MEMO), 70 MByte
(MIMO)

Availability and cost: on special request

1. Introduction

Wind flow and pollutant dispersion at any scale are decisively influenced by phenomena occurring at the next larger scale. Pollutant dispersion in the surroundings of built-up areas, such as cities or industrial areas, is governed by mesoscale wind flow systems, such as thermally induced valley winds, land- and sea-breeze circulations in coastal areas or channelled flow along valleys. In street canyons or around buildings the microscale flow plays the dominant role in the dispersion of pollutants. The microscale flow is, however, strongly affected by the mesoscale flow. In the present paper a method is presented to describe multiscale wind flow phenomena by coupling the microscale model MIMO with the mesoscale model MEMO. The coupled model system MEMO–MIMO is applied to an industrial area

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in southwestern Germany and model results are compared with available measurements. After a brief presentation of the models MEMO and MIMO the coupling method is presented. Then the application case studied is described and simulation results are compared with measurements.

2. Model descriptions

The non-hydrostatic mesoscale model MEMO was developed at the Institut für Technische Thermodynamik of the Universität Karlsruhe and the Laboratory of Heat Transfer and Environmental Engineering of the Aristotle University of Thessaloniki (Flassak, 1990; Kunz and Moussiopoulos, 1995). On the basis of the mesoscale model MEMO the microscale model MIMO was developed at the Institut für Technische Thermodynamik (Winkler, 1995). Both models have been applied successfully and evaluated in numerous applications (Moussiopoulos, 1995; Göting et al., 1995, 1997).

The prognostic models MEMO and MIMO solve numerically the conservation equations for mass, momentum, energy and additional scalars like, for example, turbulent kinetic energy. The conservation equation for mass in the anelastic form is formulated in terms of the pressure. This leads to an elliptic equation, which is solved by a preconditioned conjugate gradient method based on fast Fourier transform (Flassak and Moussiopoulos, 1989).

Both models allow non-equidistant mesh sizes in all three dimensions to increase the spatial resolution, e.g. at the ground or near buildings. To account for inhomogeneous terrain, the base equations of the mesoscale model are additionally transformed to a terrain-influenced vertical coordinate. Obstacles such as buildings are resolved directly in the microscale model, while they are parameterized by their roughness length in the mesoscale model. In both models a staggered grid (ARAKAWA C) is applied, where scalar quantities such as pressure, density and temperature are defined at the centre of a grid cell while fluxes are defined at the appropriate interfaces. Thus, the numerical scheme is conservative and does not produce artificial sources or sinks which could falsify pollutant dispersion simulations.

For the numerical treatment of advective transport a second-order flux-corrected transport (FCT) Adams–Bashforth scheme (Wortmann-Vierthaler and Moussiopoulos, 1995) or a three-dimensional second-order total-variation-diminishing (TVD) scheme can be applied. Both schemes are positive, transportive, conservative and produce only small numerical diffusion. For the calculation of turbulent diffusion K-theory is applied. The exchange coefficients are computed by an one-equation model in MEMO and by a two-equation model (standard k -, ϵ -model) in MIMO.

In both models initialization is performed using appropriate diagnostic methods based on measured data in the case of MEMO, whereas in the case of MIMO the initial state is derived from mesoscale results as described in the next section.

In principle, boundary conditions at the lateral boundaries of the mesoscale model can also be derived from measured data using a diagnostic method. Additionally, a nesting technique can be applied to enhance the horizontal resolution (Kunz and Moussiopoulos, 1997). In the latter case lateral boundary values for any grid are derived from model results on the next coarser grid. Along these lines, the horizontal resolution of MEMO may be increased in several steps to approach the horizontal resolution of MIMO. This is an important prerequisite for the coupling method. The surface temperature is calculated in MEMO from the surface energy balance taking into account radiative heating and cooling.

The formulation of the conditions at the lateral boundaries of MIMO is part of the coupling method described below. The wall function method (Launder and Spalding, 1974) is applied in MIMO for imposing wall boundary conditions, i.e. conditions at obstacle boundaries.

3. Coupling method

In this section the method for coupling the microscale model MIMO and the mesoscale model MEMO is described. Mesoscale model results are used to derive the initial state and the lateral boundary conditions of the microscale model. Feedback is not considered in the current version of the coupled system.

The coupling method consists of three elements: a three-dimensional spatial interpolation scheme, a special adjustment of values within the surface layer, and the formulation of the lateral boundary conditions to introduce the interpolated values into the microscale model.

Fig. 1 shows the vertical structure of typical numerical grids of the models MEMO and MIMO. Being of the order of several kilometres, the mesoscale domain top height exceeds by far the maximum height of the microscale model domain, which is about 100–200 m. Furthermore, the vertical resolution and the horizontal resolution are different in both model domains. Therefore, the locations where a quantity is defined differs between the model domains and a three-dimensional interpolation must be applied.

The interpolation scheme is shown schematically in Fig. 2 at the example of the scalar quantity ψ . The scalar point P of the microscale grid is surrounded by eight scalar points S of the mesoscale grid, which form a prism (dashed line). The planes (solid line) through P which are parallel to the side planes of the prism divide the volume of the prism into eight partial volumes V_i . The

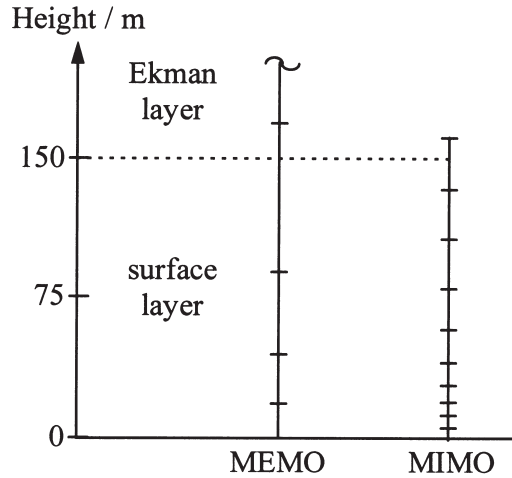


Fig. 1. Vertical structure of typical numerical grids of the models MEMO and MIMO.

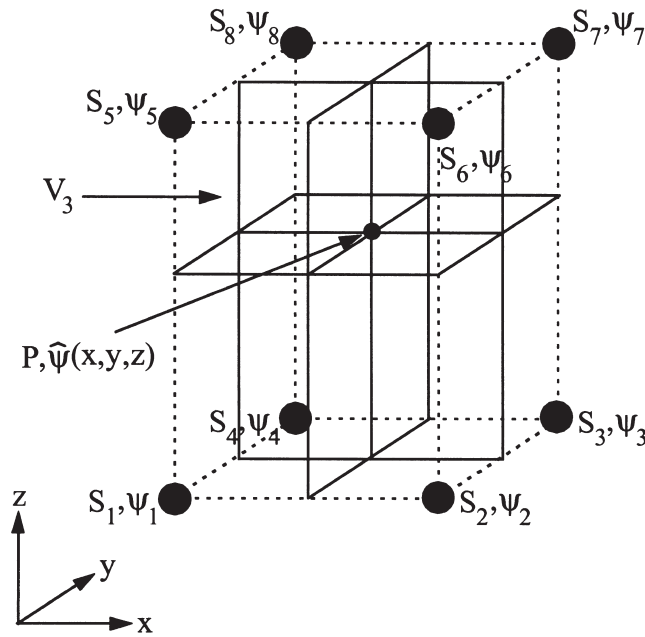


Fig. 2. Definition of quantities used for performing the three-dimensional interpolation.

fraction of a partial volume (e.g. V_3) to the whole volume is taken as the interpolation weighting factor for the value (ψ_3) which is opposite to the partial volume. Thus, the microscale value $\hat{\psi}$ is calculated by:

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

from the mesoscale values ψ_i .

Near the ground the vertical resolution of the microscale model is much higher than that of the mesoscale model (Fig. 1). Consequently, the mesoscale simulation gives only poor information about the vertical

structure of the boundary layer adjacent to the ground. Therefore, the interpolated values are adjusted using similarity theory. The microscale wind speed u at the height z in the surface layer is either calculated using the power law:

$$u(z) = u_{sl} \left(\frac{z}{z_{sl}} \right)^p \quad (2)$$

or using the logarithmic law:

$$u(z) = \frac{u^*}{\kappa} \left[\ln \left(\frac{z}{z_0} \right) + \phi_m \left(\frac{z}{L} \right) \right] \quad (3)$$

where u_{sl} is the mesoscale wind speed at the top of the surface layer z_{sl} , u^* is the friction velocity, z_0 is the roughness length and L is the Monin–Obukhov length. All these quantities are taken from the mesoscale model results. κ is the von-Kármán constant. The exponent p depends on thermal stability. Values for p are given in Table 1. The similarity function ϕ_m is calculated following Carson and Richards (1978), Hicks (1976) and Randerson (1984).

According to Tennekes and Lumley (1972) and Zeman (1979) the surface layer height z_{sl} is given by

$$z_{sl} = \begin{cases} 0.1 \cdot z_{bl} & L < 0 \\ \frac{0.1 \cdot z_{bl}}{1 + \frac{L}{z_{bl}}} & L > 0 \end{cases} \quad (4)$$

with the boundary layer height z_{bl} (see O'Brien (1970) and Zilitinkevich (1972))

$$z_{bl} = \begin{cases} \frac{\kappa \cdot u^*}{2 \cdot \Omega \cdot \sin \Psi} & L < 0 \\ \kappa \cdot \left[\frac{L \cdot u^*}{2 \cdot \Omega \cdot \sin \Psi} \right]^{0.5} & L > 0 \end{cases} \quad (5)$$

with Ω the earth's rotation frequency and Ψ the latitude. Similarity theory is only valid for horizontally homogeneous surface layers. Hence, the adjustment cannot account for the detailed structure of the microscale wind flow. The adjusted values rather serve as an estimate of the microscale solution and are used as the initial state

Table 1
Exponent for the power law

Stratification	Exponent/–
Very stable	0.419
Stable	0.369
Weakly stable	0.282
Weakly unstable	0.223
Unstable	0.205
Very unstable	0.089

and the lateral boundary values of the microscale simulation.

The interpolated wind speed is introduced into the microscale model using the expanded radiation boundary condition proposed by Carpenter (1982). Following this approach, a quantity ψ is split into two parts, a small-scale (ψ^F) and a large-scale part ($\hat{\psi}$). These two parts coincide with the microscale and the interpolated mesoscale variable, respectively. It is assumed that both parts of ψ propagate with the same phase velocity C_ψ . Hence, the time derivative of ψ^F reads

$$\frac{\partial \psi^F}{\partial t} = -C_\psi \frac{\partial \psi^F}{\partial n} + \frac{\partial \hat{\psi}}{\partial t} + C_\psi \frac{\partial \hat{\psi}}{\partial n} \quad (6)$$

with n as the coordinate perpendicular to the boundary. The phase velocity is calculated by

$$C_\psi = \left. \frac{\frac{\partial \psi^F}{\partial t}}{\frac{\partial \psi^F}{\partial n}} \right|_{B-1} \quad (7)$$

from spatial and temporal derivatives of ψ next to the boundary B . More details about the coupling method can be found in Khatib (1998). Results of a case studied with the coupled system MEMO–MIMO are shown in the next section.

4. Application

The coupled system was applied to an industrial area in southwestern Germany, namely a part of the BASF area near the Mannheim and Ludwigshafen conurbation. The cities of Ludwigshafen (Lu) and Mannheim (Ma) are located in the northern part of Baden–Württemberg where the river Neckar joins the river Rhine. The Rhine Valley is bordered by the hills of the Odenwald and the Pfälzer Wald. North of the cities are the Taunus and the Spessart mountains.

Fig. 3 shows the orography (contour interval 100 m) of the modelling domain and its surroundings. The mesoscale model MEMO was triply nested. The domain shown in Fig. 3 coincides with the coarse grid (CG) which was chosen large enough for taking into account influences of the Taunus and the Spessart on the local wind flow. The frames in Fig. 3 indicate the location of the medium (MG) and the fine (FG) grids. The buildings considered in the microscale simulations are shown in Fig. 4. The figure coincides with the microscale model domain. The streets are shown by dashed lines. Numerical specifications such as the number of grid points and computing time are given in Table 2.

The mesoscale simulations were performed for a per-



Fig. 3. Orography of the coarse grid modelling domain (contour interval 100 m).

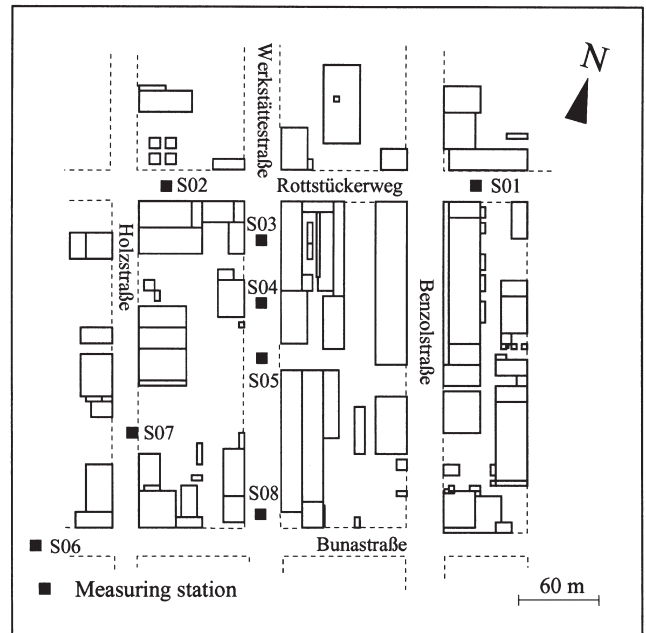


Fig. 4. Microscale modelling domain with the locations of the measuring stations (solid squares).

iod of 24 hours, a typical day in spring. Microscale wind flow was simulated for four typical times of day: morning (9:00), noon, afternoon (15:00) and early night (21:00). The near-ground flow fields of both mesoscale and microscale simulations are discussed in Khatib (1998). In the remainder of this paper only comparisons between measured and predicted values are presented.

A basic difficulty when evaluating a coupled mesos-

Table 2
Numerical specifications

Simulation		No. of grid points	cpu time (min) ^a
MEMO	CG	50×50×30	360 ^b
	MG	60×60×30	
	FG	60×60×30	
MIMO	9:00	120×120×50	48
	12:00	120×120×50	70
	15:00	120×120×50	110
	21:00	120×120×50	78

^a On the vector processor Fujitsu vpp 300/16 of the Universität Karlsruhe.

^b Total simulation time for the three grids.

cale–microscale modelling system is that available measured data can hardly reflect appropriately phenomena occurring at both scales. Field measurements are usually performed with the intention of measuring the mesoscale flow, if possible without any influence of local effects. Microscale flow measurements, on the other hand, are very often carried out in the interior of street canyons and are therefore in general not markedly affected by mesoscale influences. Manier et al. (1987) performed a field measuring campaign on and near the BASF area with the aim of measuring both the regional flow at three measuring stations installed in the countryside surroundings of the industrial area and the local flow at eight stations located in the industrial area. The location of the latter eight stations is denoted on Fig. 4 by solid squares. As station S06 is very close to the boundary of the domain it is omitted in the comparison.

Tables 3 and 4 show the measured and the predicted mesoscale and microscale velocities, respectively. The predicted mesoscale values are averaged over the simulated 24 hours, the microscale ones are averages over the results for the considered four times of the day. The measured values correspond to annual averages.

The predicted mesoscale wind speed and wind direction (Table 3) are in good agreement with the observed values. The simulations reproduce even the fact that the observed wind speed at station Maudach to the south of the industrial area is slightly higher than that at the other two stations.

The results of the microscale simulations (Table 4)

Table 3
Measured and predicted mesoscale wind flow

Station	Measured		Predicted	
	<i>u</i> (m/s)	ϕ (deg)	<i>u</i> (m/s)	ϕ (deg)
Petersau	3.10	175–215	3.06	180–212
Roßlache	3.10	150–220	3.04	183–220
Maudach	3.20	150–220	3.48	200–235

Table 4
Measured and predicted microscale wind flow

Station	Measured		Predicted	
	<i>u</i> (m/s)	ϕ (deg)	<i>u</i> (m/s)	ϕ (deg)
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
S07	1.70	175–202	2.07	186–197
S08	1.72	150–250	2.36	205–234

appear to be slightly higher than the corresponding measurements. This overestimation may be a consequence of the fact that the modelling domain covers only a sector of the industrial area. Thus, the deceleration by the buildings may in reality be larger than predicted by the model.

The wind velocities at stations S01, S02, S03, S04 and S05 are fairly similar. At stations S07 and S08 the wind speeds are higher compared to the other stations. This is associated with the fact that the main wind flow comes from a southwesterly direction. Stations S07 and S08 are at the southwestern boundary where the inflow is nearly unaffected by the influence of the buildings.

5. Conclusions

A method was presented to couple the microscale flow model MIMO with the mesoscale flow model MEMO. The purpose of this coupling was to introduce the influences of regional flow phenomena into microscale wind flow simulations. The coupled system was applied to predict the wind flow over an industrial area. Predicted results are in good agreement with measurements. The method is suitable to generate realistic initial and boundary values for microscale simulations. The method can therefore be applied when the flow over built-up areas is to be simulated but no observational evidence about the wind flow in the surroundings is available.

Acknowledgements

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