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Urban air pollution based on a high resolution digital elevation map

Summary

A dispersion model which is suitable for the estimate of traffic-derived air pollution has been developed, based on a high resolution map which provides information on the height of buildings within the urban area and of traffic data continuosly monitored in several points. In the present case concentration data of several pollutants measured through air quality stations located within the urban area of Trento are available. On the other hand only one reliable weather station is presently active within the urban area. However, for this kind of analysis which refers to low level emission sources, traffic conditions turn out to be much more important than meteorological factors in determining air pollution. The calculus domain along the vertical direction is divided in two parts: in the lower layer the pollutant is assumed to spread only due to diffusion, while in the upper layer, whose lower limit is fixed by the average height of the buildings, advection is also taken into account. The average wind speed above the buildings' level is supposed to be uniform in space. The diffusion coefficient in the lower layer results from three contributions: the first is related to atmospheric stability, the second is the mechanical turbulence induced by the transit of motorvehicles, the third term arises from a globl estimate of the effect of the flow field within the urban fabric, which is not directly computed in case of lack of spatially distributed wind data.

Procedure

Meteorological data
- wind speed and direction
- stability class

Traffic data

Digital elevation map

COPERT III procedure

Emissions

Dispersion model

Pollutant concentration

In order to obtain concentation maps at urban scale, detailed datasets are required, both for the structure of the city and for emissions, as air pollution comes out to be strongly related to urban traffic cycle.

COPERT III scheme:

Fuel Variables
- consumption
- specifications per fuel type

Activity Data
- number of vehicles per vehicle category
- distribution of the vehicle fleet into different exhaust emission legislation classes
- mileage per vehicle class
- mileage per road class

Driving Conditions
- average speed per vehicle type and per road

Other Variables
- climatic conditions
- mean trip distance
- evaporation distribution

Emission Factors
- per type of emission (hot, cold, evaporation)
- per vehicle class
- per road class

COPERT procedure estimates, on the basis of fuel consumption, emissions of all regulated air pollutants (CO, NO_x, VOC, PM_{10}) produced by different vehicle categories: passenger cars, light duty vehicles, heavy duty vehicles, mopeds and motorcycles.

Estimated emissions are divided in three source types:
- hot emissions = produced during thermally stabilised engine operation
- cold emissions = occurring during engine start (cold-start and warming-up effects)
- evaporation = NMVOC emissions due to fuel evaporation

Total emissions are calculated as the product of activity data and speed-dependent emission. [2]

Finite differences dispersion model scheme:

The emissions provided from the COPERT procedure [g/(km h)] are converted to emission per unit width (sidewalks not included) [g/(m² s)]. The dispersion equation is solved by means of a finite differences explicit scheme, using a second order scheme for advection term in order to achieve better accuracy: the Lax Wendroff method drastically reduces numerical diffusion [3].

The dispersion equation is used with 2D advection and 3D diffusion

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = K_x\frac{\partial^2 C}{\partial x^2} + K_y\frac{\partial^2 C}{\partial y^2} + \frac{\partial^2}{\partial z^2}\left(K_z\frac{\partial C}{\partial z}\right) + S'$$

An explicit method is used for discretization

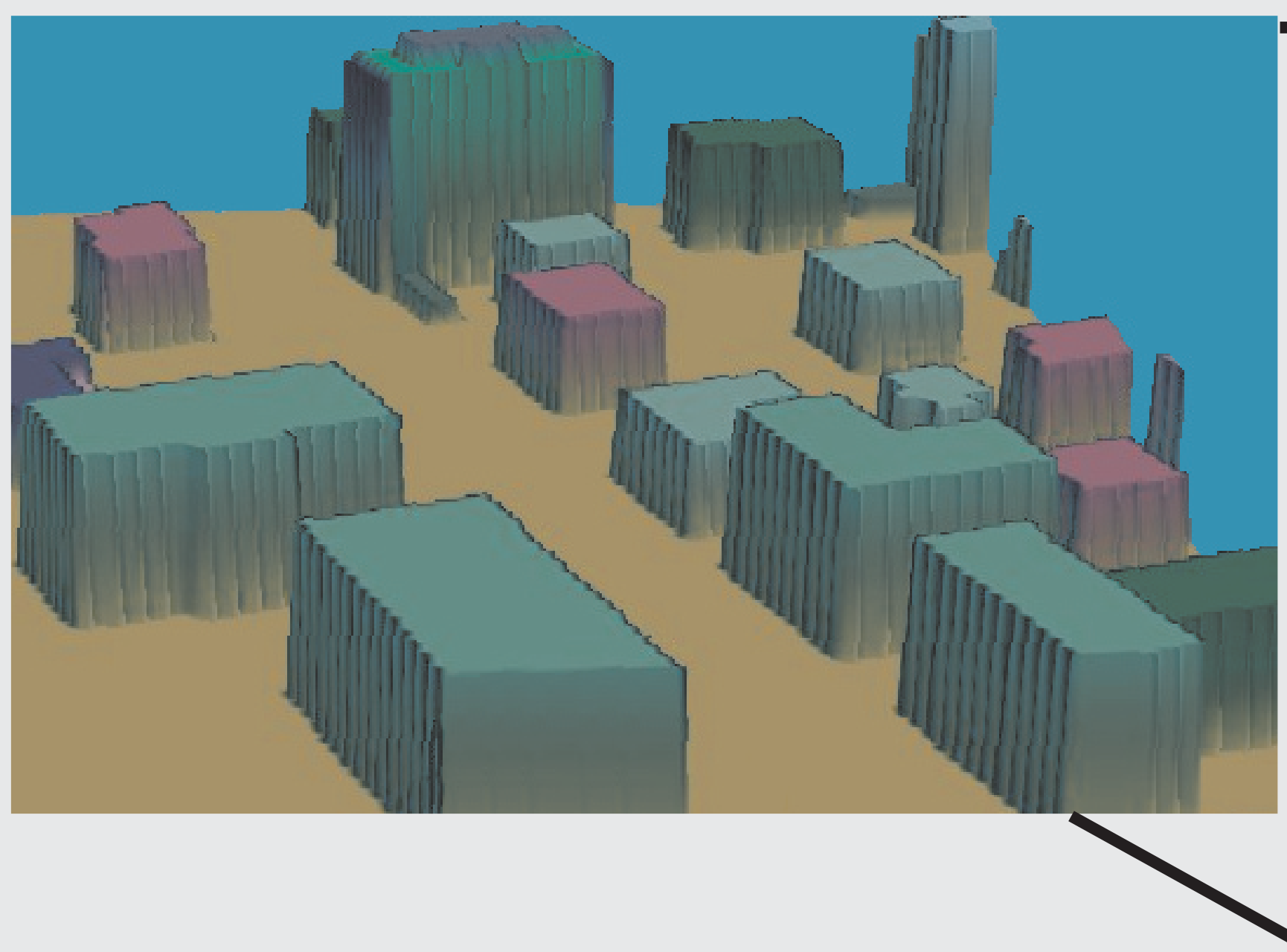
$$C^{n}_{ijk} = C^{n-1}_{ijk} + \Delta t\cdot\underbrace{\left(Ax^{n-1}_{ijk}+Ay^{n-1}_{ijk}\right)}_{\text{advection term}} + \Delta t\cdot\underbrace{\left(Dx^{n-1}_{ijk} + Dy^{n-1}_{ijk} + Dz^{n-1}_{ijk}\right)}_{\text{diffusion term}} + \underbrace{\Delta S^{n-1}_{ijk}}_{\text{source term}}$$

Diffusion term: diffusivity is supposed to vary only along z direction

$$\begin{cases} Dx_{ijk} = \frac{Kx_k}{\Delta x^2}\left(C_{i-1jk} - 2C_{ijk} + C_{i+1jk}\right) \\ Dy_{ijk} = \frac{Ky_k}{\Delta y^2}\left(C_{ij-1k} - 2C_{ijk} + C_{ij+1k}\right) \\ Dz_{ijk} = \frac{1}{\Delta z^2}\left[\frac{Kz_{k-1}+Kz_k}{2}\left(C_{ijk-1} - C_{ijk}\right) + \frac{Kz_k+Kz_{k+1}}{2}\left(C_{ijk} - C_{ijk+1}\right)\right] \end{cases}$$

Parametrizations depending on air stability are used for vertical diffusivity coefficient K_z. Horizontal diffusivity coefficients K_x and K_y are assumed to be proportional to K_z; c_1 is used as a calibration parameter [1].

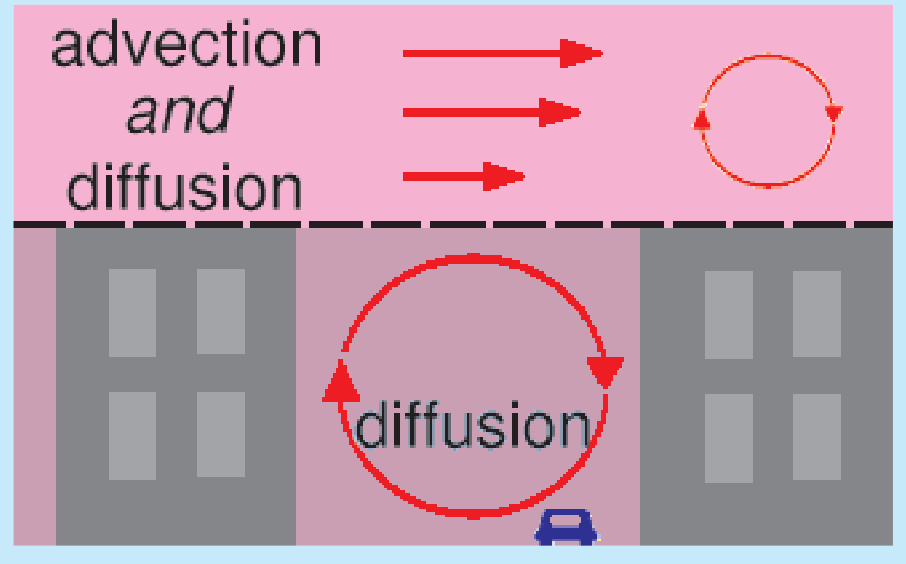
$$K_z(z) = K_{z0}\cdot\left(\frac{z}{h_0}\right)^{\beta} \quad ; \quad K_{z0} = k^2\frac{u_0\cdot h_0}{G} \quad ; \quad K_{x,y} = c_1\cdot K_z$$

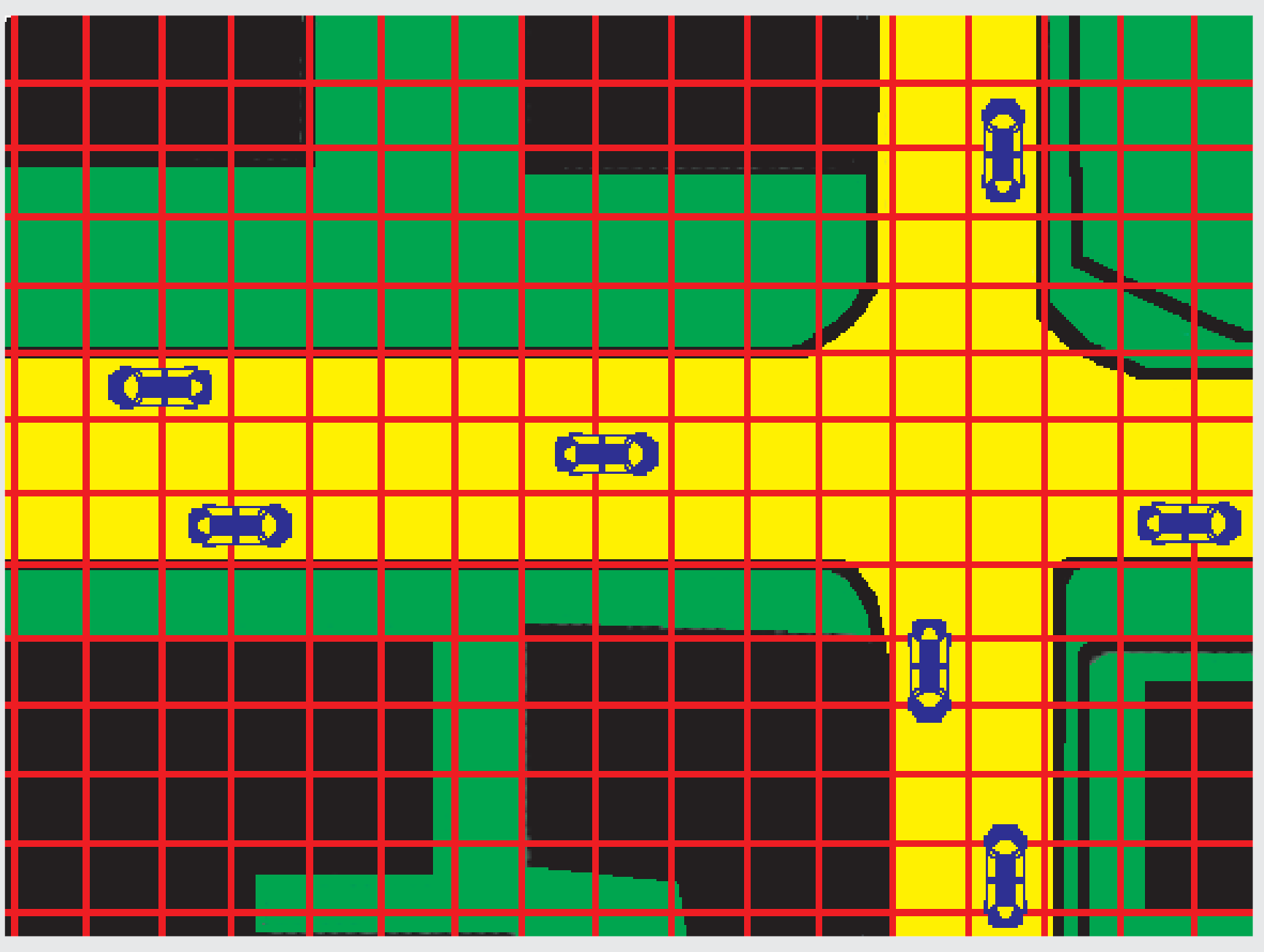


A regular grid is created starting from the digital elevation map; three types of cells are present:
- 🟨 = domain cells where source term is positive (streets)
- 🟩 = domain cell where source term is null (sidewalks, parks, parking areas, streets with no traffic)
- ⬛ = cellls not belonging to computational domain (buildings)

Diffusion in source cells is supposed to be strongly related to mechanical turbulence induced by vehicles; thus these cells are considered to be completely mixed at emission time.

For simplicity only diffusion term is considered inside the urban fabric, while both advection and diffusion are computed above the buildings' level. This hypothesis seems to be accettable only when the urban structure presents a "canyon" behaviour [4] or when the wind speed is low enough so that advection is not dominant along the street paths.





Advection term: a second order conservative scheme (Lax - Wendroff method) is used in order to reduce numerical diffusion [3]

$$\begin{cases} Ax_{ijk} = -\frac{1}{\Delta t}\left|Co_{x,ijk}\right|\left\{\left[C_{ijk} - C_{Ljk}\right] + \frac{1}{2}\left[\Phi_{x2,ijk}\left(1 - \left|Co_{x,ijk}\right|\right)\left(C_{Mjk} - C_{ijk}\right) - \Phi_{x1,ijk}\left(1 - \left|Co_{x,ijk}\right|\right)\left(C_{ijk} - C_{Ljk}\right)\right]\right\} \\ Ay_{ijk} = -\frac{1}{\Delta t}\left|Co_{y,ijk}\right|\left\{\left[C_{ijk} - C_{iPk}\right] + \frac{1}{2}\left[\Phi_{y2,ijk}\left(1 - \left|Co_{y,ijk}\right|\right)\left(C_{iQk} - C_{ijk}\right) - \Phi_{y1,ijk}\left(1 - \left|Co_{y,ijk}\right|\right)\left(C_{ijk} - C_{iPk}\right)\right]\right\} \end{cases}$$

where:

$$\underbrace{\begin{cases} \Phi_{x1,ijk} = max\left(0, min\left(1, \frac{C_{Ljk}-C_{Njk}}{C_{ijk}-C_{Ljk}}\right)\right) \\ \Phi_{x2,ijk} = max\left(0, min\left(1, \frac{C_{ijk}-C_{Ljk}}{C_{Mjk}-C_{ijk}}\right)\right) \\ \Phi_{y1,ijk} = max\left(0, min\left(1, \frac{C_{iPk}-C_{iRk}}{C_{ijk}-C_{iPk}}\right)\right) \\ \Phi_{y2,ijk} = max\left(0, min\left(1, \frac{C_{ijk}-C_{iPk}}{C_{iQk}-C_{ijk}}\right)\right) \end{cases}}_{\text{"minmod" limiter}} \quad ; \quad \underbrace{\begin{cases} Co_{x,ijk} = u_{ijk}\frac{\Delta t}{\Delta x} \\ Co_{y,ijk} = v_{ijk}\frac{\Delta t}{\Delta y} \end{cases}}_{\text{Courant numbers}} \quad ; \quad \begin{cases} L = i - sign(u) \\ M = i + sign(u) \\ N = i - 2\cdot sign(u) \\ P = j - sign(v) \\ Q = j + sign(v) \\ R = j - 2\cdot sign(v) \end{cases}$$

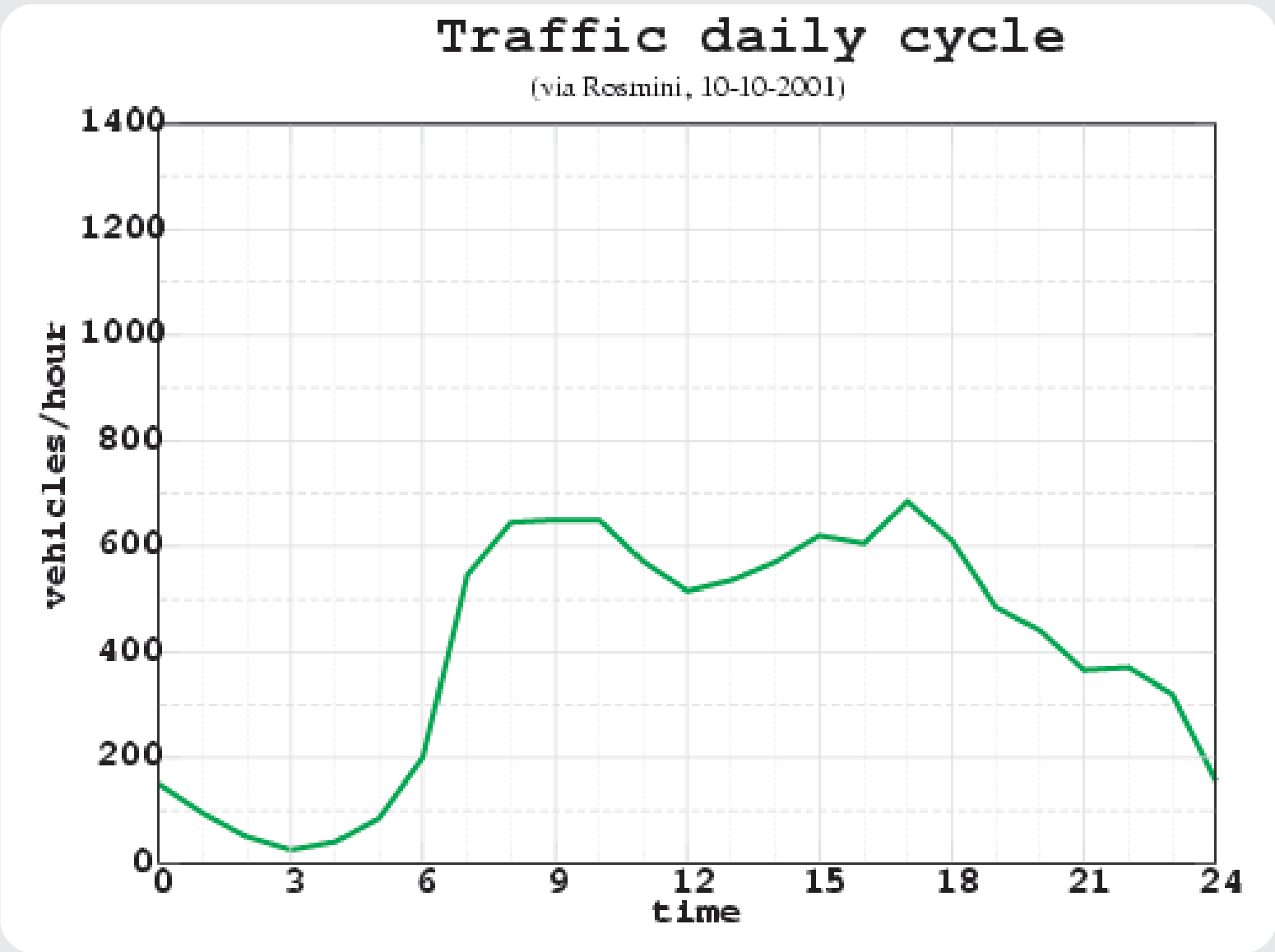
List of symbols:

C = concentration [g/m³]
S' = source term [g/(m³ s)]
K_x, K_y, K_z = diffusivity along x, y, z direction [m²/s]
D_x, D_y, D_z = diffusion term along x, y, z direction [g/(m³ s)]
A_x, A_y = advection term along x, y direction [g/(m³ s)]
h_0 = reference height [m]
K_{z0} = diffusivity at reference height [m²/s]
u_0 = wind speed at reference height [m²/s]
Co_x, Co_y = Courant number along x, y direction [-]
G, β = functions depending on stability class (or Monin Obukhov lenth) [-]
k = Von Karman constant (=0.4)
Φ = "minmod" limiter function for dumping of 2nd order scheme numerical oscillation

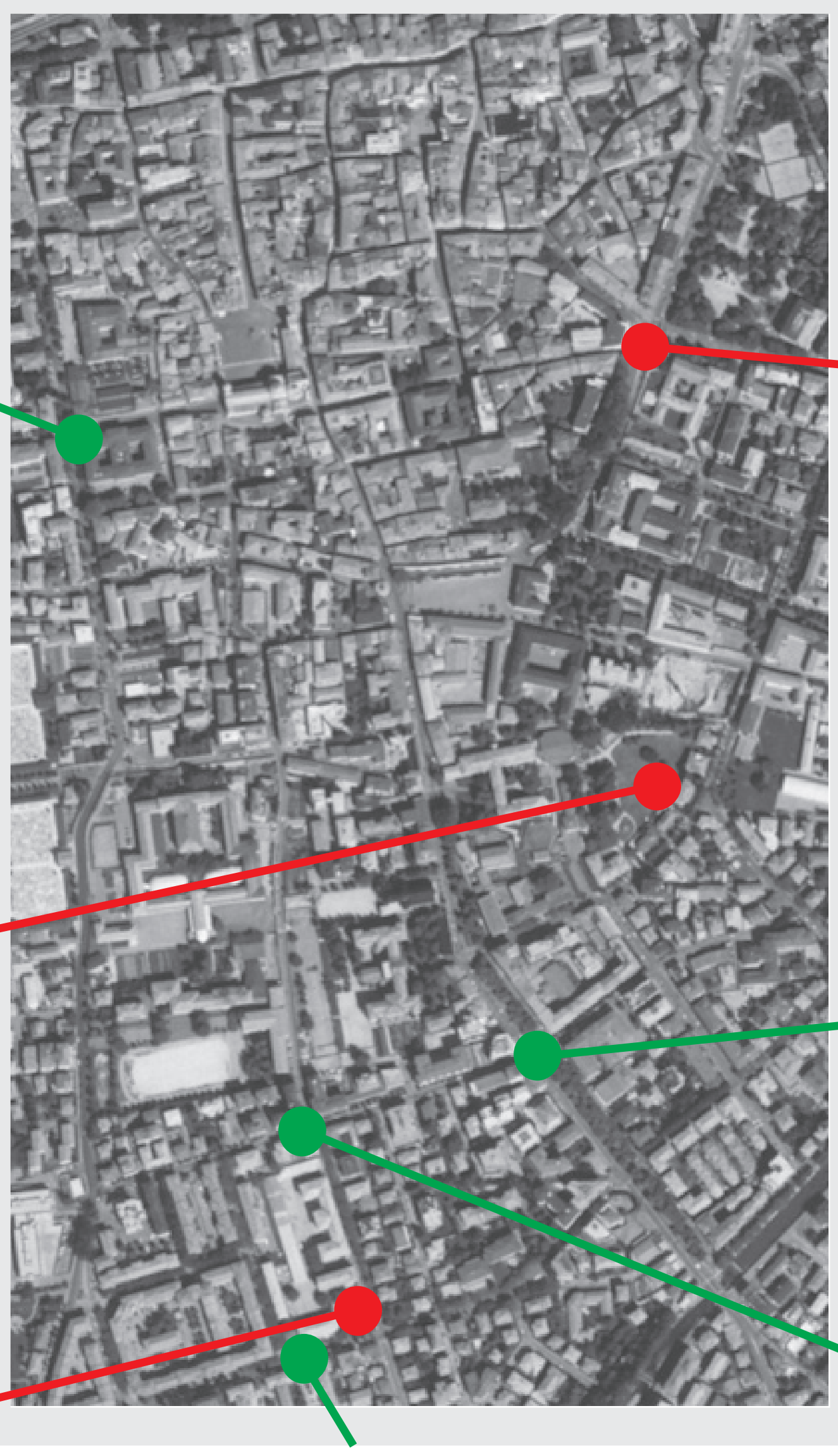
Numerical stability condition:

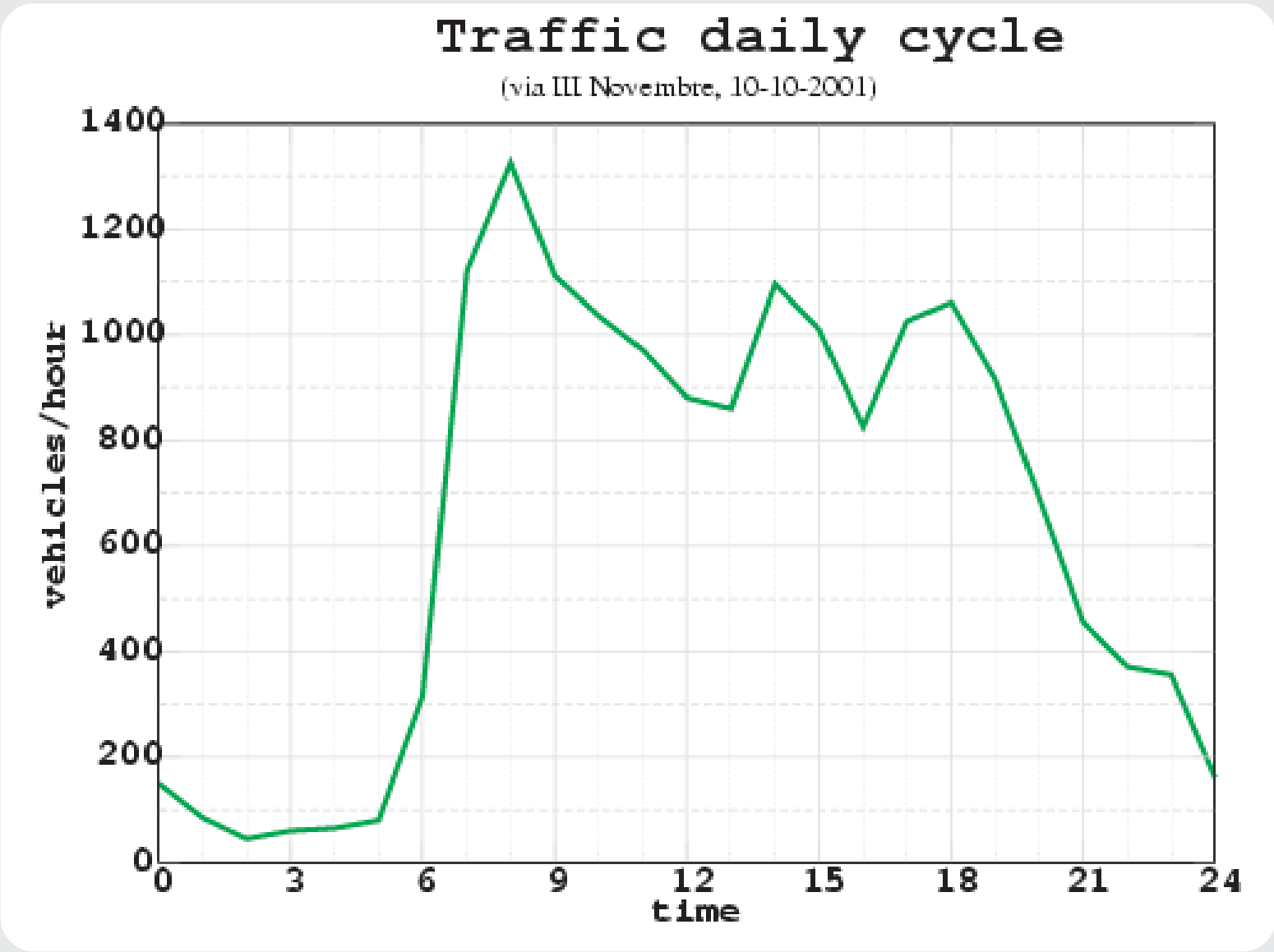
$$\Delta t \le \frac{1}{\frac{|u|}{\Delta x} + \frac{|v|}{\Delta y} + \frac{2K_x}{\Delta x^2} + \frac{2K_y}{\Delta y^2} + \frac{2K_z}{\Delta z^2}}$$

A case study: application to the town of Trento (Italy)



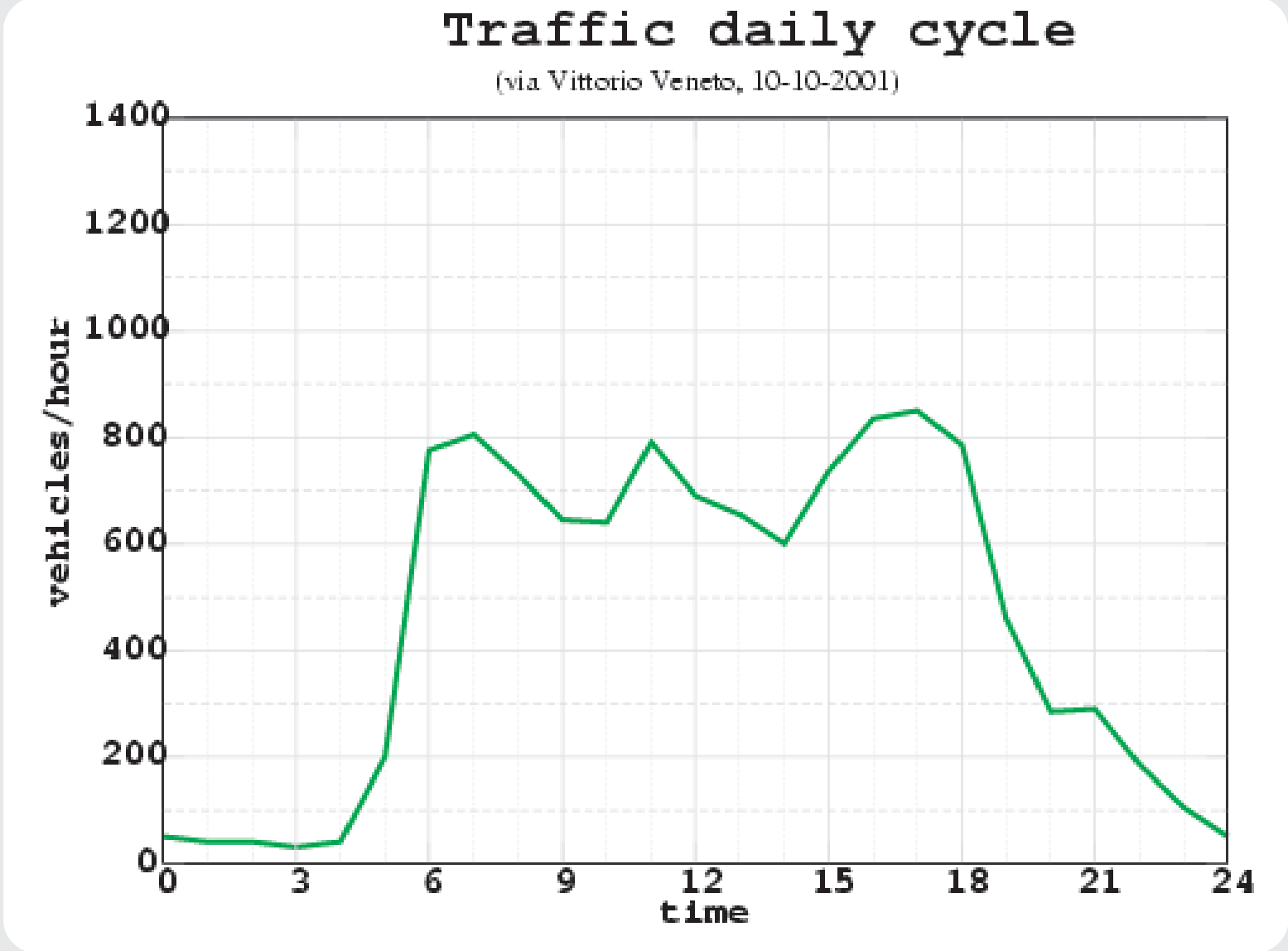
Input data and

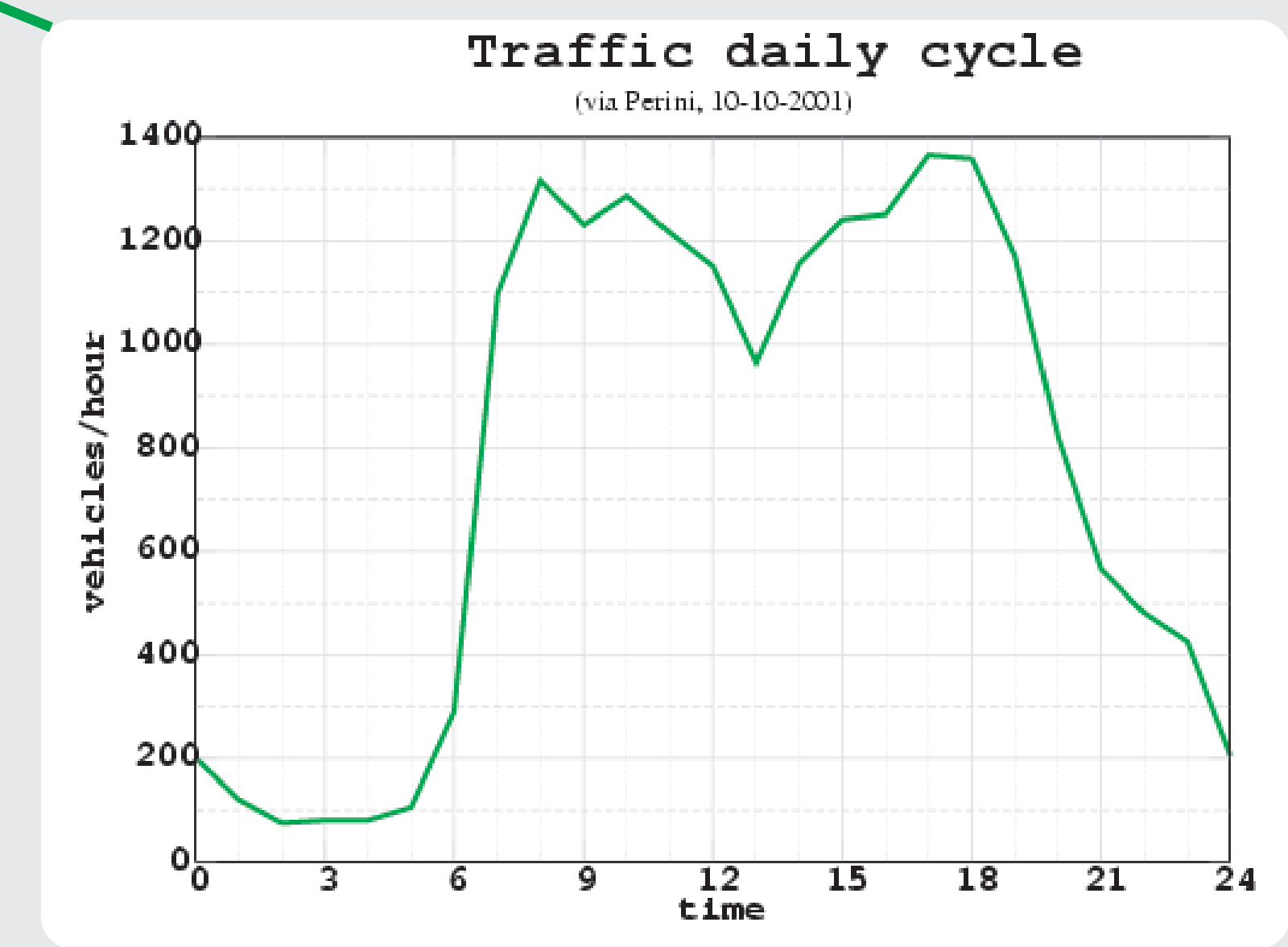


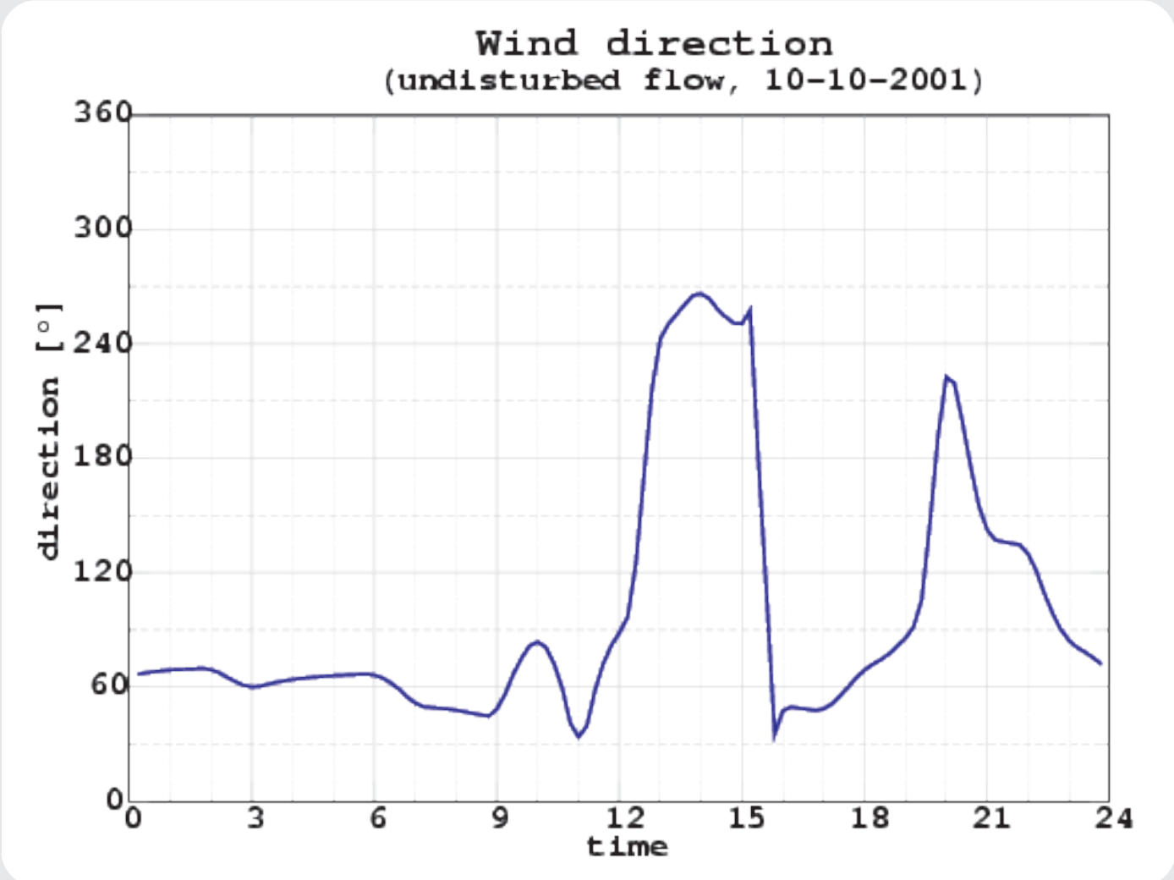


Comparison between monitored (black lines) and computed concentration (red lines) and examples of traffic daily cycle registred in 4 of about 100 measurement points (green lines).

Traffic data, air quality data and digital elevation map of the town with 1 m resolution were made available by the local Environmental Protection Agency.



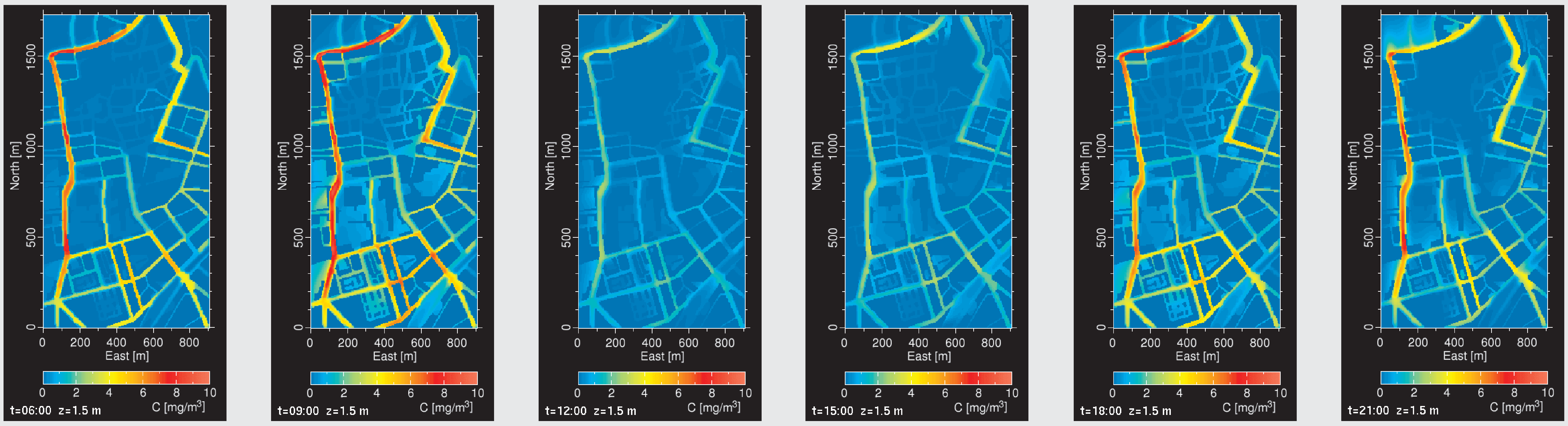




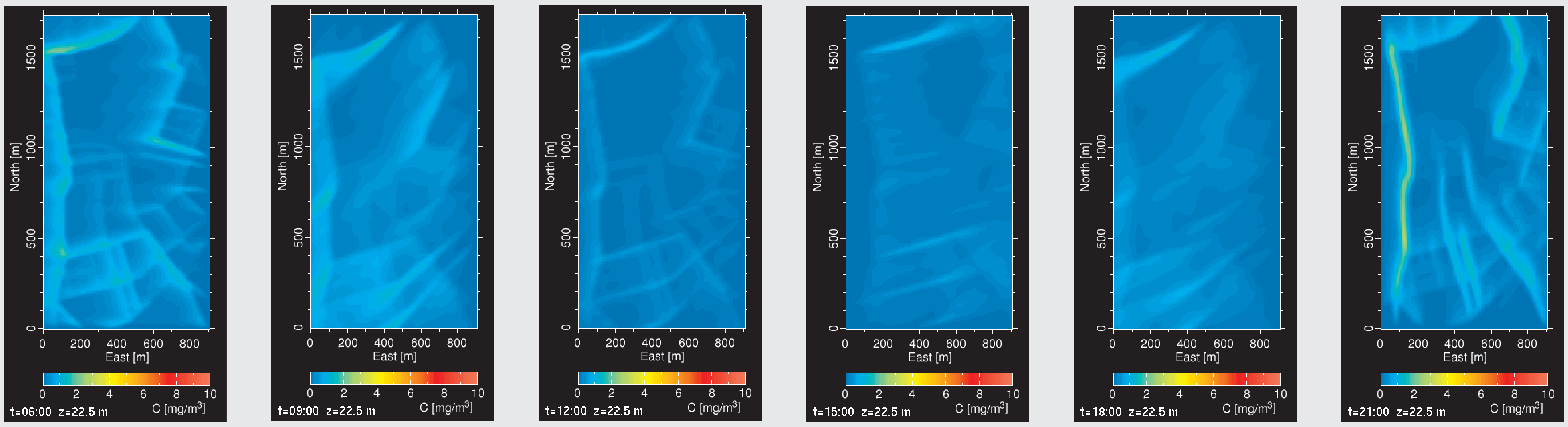
Concentration maps, daily evolution:

Carbon monoxide was used as tracer in the test; anyway, any other pollutant considered in the COPERT procedure can be used; reactive pollutant can be simulated only on a small temporal scale. A grid size of $\Delta x = 5$ m, $\Delta y = 5$ m and $\Delta z = 3$ m was chosen, while the the time step Δt was variable according to stability condition.

CO concentration at z=1.5 m (ground level)



CO concentration at z=22.5 m (above top building level)



Discussion

Concentration at ground level within urban network mainly depends on traffic conditions; however, highly unstable atmospheric conditions can reduce significantly the values of concentration. Meteorological conditions mainly affect the pollutant concentration in the far field. High spatial resoultion is needed in computation in order to catch the spatial varaibilty of concentration. The model is applicable only when a large amount of data describing traffic and streets layout is available.

References

[1] R. Sozzi, T. Georgiadis, M. Valentini, ***Introduzione alla turbolenza atmosferica***, ed. Pitagora, 2002
[2] L. Ntziachristos, Z. Samaras, ***Computer programme to calculate emissions from road transport. Methodology and emission factors***, European Environment Agency, 2000
[3] R.J. Leveque, ***High resolution algorithms for advection in incompressible flow***, J. Numer. Anal., vol. 33, pp. 627-665, 1996
[4] T.R. Oke, ***Boundary Layer Climate***s, Routledge, New York, 1987