Mesoscale modeling of the urban atmosphere

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The Ideal City,
Piero della Francesca, c. 1470,
Galleria Nazionale, Urbino, Italy
Which are the main interactions between a city and the atmosphere?
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Buildings reduce mean wind speed and generate turbulence and small scale circulations at the scale of the buildings (e.g. canyon vortex)
Which are the main interactions between a city and the atmosphere?

The different orientations and the different thermal properties of the urban surfaces and the anthropogenic heat sources generate strong spatial variability of the heat fluxes exchanged with the atmosphere.
Which are the main interactions between a city and the atmosphere?

Pollutant emissions from traffic and other human activities modify the composition of the urban atmosphere.
All these phenomena are connected
Heat exchanges between buildings and atmosphere are influenced by wind speed
Wind patterns in the canopy depend on the turbulent structure of the atmosphere, which is in turn influenced by heat fluxes.
Pollutant dispersion is determined by wind and turbulence.
Pollutant concentration (aerosols) may impact the radiation fluxes, and consequently the surface heat fluxes.
Urban climate affects energy consumption (heating, air conditioning).

Energy production (if from fossil fuels) may affect pollution.
Urban climate  

Electric Utility Demand Depends on Air Temperature

Load (MWh)

Mean Daily Temperature (°C)

Energy consumption

Global warming
Emissions are function of temperature

Biogenic emissions

Human related emissions:
Power plant emissions, motor vehicle emissions, etc. are function of temperature.
All these phenomena are important for citizens

Air quality

Pedestrian wind

Urban climate
The number of citizens increases every day.

The number of megacities (more than 10 millions of inhabitants) also increases:
In 1950, there were only two megacities in the world (New York and Tokyo with 12.4 and 11.3 milions).
In 2004 there were 20 megacities with 283 milions of inhabitants in total.
(UN, 2004).
All these phenomena are the results of human activity. They can be modified.

A significant part of research on urban atmosphere has been carried out using numerical models.

A big advantage of using numerical models is that they can be used to forecast the future, or to investigate possible future scenarios (what if…). Such peculiarity makes numerical models a an interesting tool that can be used in many practical applications to help to take decisions.
What type of models should be used?

Mesoscale models
Urban areas are very complex

The scale of the heterogeneity is 1-10 metres

The resolution of a mesoscale model is of the order of one kilometre.

*How to model the effects of atmospheric features induced by urban heterogeneities with such resolution?*

A parameterization is needed.
Factors influencing the way urban surfaces are represented in mesoscale models

- **Type of application**
- **Computational power available**
- **Parameterization of urban areas**
- **Scientific knowledge**
Philosophy of the parametrizations:

Advantage: every building behaves in the same way and also every street behaves in the same way. By computing the fluxes for one building and for one street, the fluxes for the whole grid cell can be easily estimated.

The idealized morphology should produce the same spatially averaged fluxes of heat and momentum, and the same vertical profiles of the spatially averaged variables.
Example BEP (Building Effect Paramterization, Martilli et al. BLM 2002)

Drag Wake Radiation

Momentum Turbulence Heat

Turbulent scheme of Bougeault and Lacarrere, (1989)
BEP was implemented in FVM (swiss model), WRF (NCAR), LM (Lokall Model), HIRLAM (Danish version).

Examples: 2D tests with WRF over flat terrain with a city in the middle of the domain.

\[ \Delta x = 2 \text{km}, \quad \Delta z_{\text{min}} = 5 \text{m} \]
The model is able to simulate the Urban Heat Island, and the elevated inversion above the city, something that has been observed in several field campaigns.

Sapporo (Uno et al. 1988) \( Z_h = 40-60 \text{m}, Z_t = 90-100 \text{m} \)

St. Louis (Godowitch et al. 1985) \( Z_h = 150 \text{m}, Z_t = 325+/ -105 \text{m} \)

An urban “hot” plume forms, and the presence of the city modifies the height of the Planetary Boundary Layer. The model reproduces a reduction of wind speed in the lowest levels above the city, and an acceleration aloft.
Deficiency of the model in the estimation of anthropogenic heat fluxes

Development of a simple building energy model (BEM) linked to an Urban Canopy Parameterization (BEP).

(Salamanca et al. TAC, 2009, Krpo et al. BLM, 2010)

Air conditioning (heating)

Air conditioning (cooling)

Heat conduction through walls

Indoor heat sources (occupants, equipments)

ventilation

Solar radiation through windows

Improve the estimate of the anthropogenic fluxes. Estimate energy consumption related to meteorology (air conditioning and heating).
Test 1D of BEP+BEM

- City of Basel for the BUBBLE experiment.
- Availability of measurements of Heat Fluxes above the urban canyon, and measurements of internal air temperature (air conditioning working).
- Two periods of summer 2002.
During both day and night, the simulations with air conditioning improve the results compared with the old scheme.
BEP-BEM implemented in a mesoscale model (WRF), and run over Houston.
### RMSE for 2m Air temperature

#### 31st Aug.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>BEP</th>
<th>BEP+BEM</th>
<th>BEP</th>
<th>BEP+BEM</th>
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<tbody>
<tr>
<td>C01</td>
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<tr>
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<td>0.9693</td>
<td>1.5736</td>
<td>0.8885</td>
</tr>
</tbody>
</table>

#### 25th Aug.

**West-East (110 km)**

*Monitoring stations location*
Impact of anthropogenic heat (emissions of heat from Air conditioning).

T2(AH)−T2(no AH) at 0300 LST (26 August) for the NUDAPT case
## Energy consumption

<table>
<thead>
<tr>
<th>Daily energy consumption in MWh</th>
<th>NUDAPT</th>
<th>WRF</th>
</tr>
</thead>
<tbody>
<tr>
<td>25th August</td>
<td></td>
<td>34946</td>
</tr>
<tr>
<td>31st August</td>
<td></td>
<td>45058</td>
</tr>
</tbody>
</table>

Daily energy consumption for **space cooling**

<table>
<thead>
<tr>
<th>Top down</th>
<th>Bottom up</th>
</tr>
</thead>
<tbody>
<tr>
<td>45853</td>
<td>45483</td>
</tr>
</tbody>
</table>

Daily averaged energy consumption from **all sources** (space cooling, lighting and appliances, and water heating) for the city of Houston for the month of August (Heiple and Sailor, 2008).

- Nationally, about half of the annual energy consumed in commercial buildings is for heating ventilation or air conditioning, (probably higher for Houston in summer).
- Heiple and Sailor estimation based on climatic data, but 31st of August hotter than average (41 C vs 33 C max temp).
A step towards a tool to evaluate urban development scenarios

A model for urban growth and regional development

Climate model

Mesoscale Meteorological Model

Urban parameterization with building energy model

Dispersion and photochemical model

Traffic model

Emission model

Air quality

Urban climate

Energy consumption
Urban and regional simulations: The MOLAND model

- Land use map
- Accessibility
- Zoning status (policy)
- Suitability
- Socio-economic data

GIS environment

- Scenarios: future land use maps

Input

Cellular Automata-based model

Output
Urban and regional simulations: The MOLAND model

Simulation: MADRID 2020

Business as usual
Compact
Sprawled multi-nodal
There is a remarkable relation between the population density and energy consumption for transport.

Can we find something similar for energy consumption for air conditioning/heating?

Can we find a relation between urban structure, energy consumption and urban climate?
Series of idealized 2D simulations with WRF:

Characteristics of the cities studied:
• 10 millions inhabitants (megacity).
• 5 cities with different size and population density.
• Occupancy: 1 person every 50m².
• Building size B=20m.
• Albedo of roofs and walls 0.2.
• Internal target temperature: 23 Celsius

Summer case (21st of June), Latitude 45N

1 m/s

200km

Horizontal resolution 1km
### Characteristics of the five cities

<table>
<thead>
<tr>
<th>City size (km)</th>
<th>Population density (inhabitants/hectare)</th>
<th>Building height distribution</th>
<th>Street width (m)</th>
<th>Urban fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10</td>
<td>100% <strong>5m</strong></td>
<td>140</td>
<td>40%</td>
</tr>
<tr>
<td>40</td>
<td>62</td>
<td>100% <strong>5m</strong></td>
<td>25</td>
<td>70%</td>
</tr>
<tr>
<td>25</td>
<td>160</td>
<td>20% 5m 60% <strong>10m</strong> 20% 15m</td>
<td>30</td>
<td>100%</td>
</tr>
<tr>
<td>20</td>
<td>250</td>
<td>20% 10m 60% <strong>15m</strong> 20% 20m</td>
<td>28</td>
<td>100%</td>
</tr>
<tr>
<td>16</td>
<td>391</td>
<td>20% 15m 60% <strong>20m</strong> 20% 25m</td>
<td>21</td>
<td>100%</td>
</tr>
</tbody>
</table>
Results

- Energy consumption from air conditioning
- Energy consumption from transport

• For relatively densely populated cities the energy consumption from air conditioning can be even higher than the energy consumption for transport.
• Medium dense cities consume more energy for a.c. than low and high dense cities.
Why?

More green areas, lower temperatures

Less surfaces to receive solar radiation
What’s the relationship between population density and climate?

Time integral of the temperatures above 30°C multiplied by the number of people in the grid cell.

The densest is the city, the hottest is the climate (Summer at 45°N!!).
Can a change in albedo of roofs and walls improve energy consumption and climate for a medium dense city?

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<tr>
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<tbody>
<tr>
<td>25</td>
<td>160</td>
<td>20% 5m 60% 10m 20% 15m</td>
<td>30</td>
<td>100%</td>
</tr>
</tbody>
</table>

Albedo of roofs and walls

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
</tr>
<tr>
<td>0.20</td>
</tr>
<tr>
<td>0.35</td>
</tr>
<tr>
<td>0.50</td>
</tr>
</tbody>
</table>
An increase of the albedo of roofs and walls can reduce the energy consumption and improve the urban climate.
Can a change in vegetation fraction improve energy consumption and climate for a medium dense city?

<table>
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<tr>
<th>City size (km)</th>
<th>Population density (inhabitants/hectare)</th>
<th>Street width (m)</th>
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<td>25</td>
<td>160</td>
<td>30.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building height distribution</th>
<th>Urban Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% 5m</td>
<td>1.0</td>
</tr>
<tr>
<td>60% 10m</td>
<td></td>
</tr>
<tr>
<td>20% 15m</td>
<td>0.66</td>
</tr>
<tr>
<td>60% 15m</td>
<td></td>
</tr>
<tr>
<td>20% 20m</td>
<td>0.5</td>
</tr>
<tr>
<td>60% 20m</td>
<td></td>
</tr>
<tr>
<td>20% 25m</td>
<td>0.4</td>
</tr>
<tr>
<td>60% 25m</td>
<td></td>
</tr>
<tr>
<td>20% 30m</td>
<td></td>
</tr>
</tbody>
</table>
An increase of the vegetation fraction can reduce the energy consumption and improve the urban climate.
More elements should be considered:

- Air humidity
- Air quality
- Winter conditions
- Radiant temperature
Conclusions

There are complex interactions between air quality, urban climate, and energy consumption related to climate (space heating/cooling).

Mesoscale atmospheric models with detailed urban canopy parameterizations are becoming an appropriate tool to investigate these interactions.

In connection with other models, they can be used to design and evaluate urban structure modification strategies (including urban future developments) to improve urban climate, air quality and energy consumption.
Thank you!

Le citta’ invisibili,
Colleen Corradi Brannigan