URBAN METEOROLOGY & TEB

Valéry MASSON
Urban Climate
Urban Heat Island

→ city up to 10K warmer by clear nights
→ Of the order of 1K by day

Observed minimal temperatures near Paris (Ile de France: heat wave 2003)

From Oke, 1987
Characteristics of the Urban atmosphere

- **URBAN BOUNDARY LAYER**
  Boundary Layer above the city

- **URBAN HEAT ISLAND**
  Temperature difference between city and countryside

- **URBAN BREEZE / URBAN PLUME**
Physical processes
Physical processes: where do the heat come from?

- CO2 emissions → Global warming
- Urban CO2 emissions → Urban warming (urban heat island)
- Trees in cities → CO2 absorption → Smaller Urban Heat Island

NO!! This is wrong

Concentration en CO2, source NASA
The physical processes

- **Evaporation Vegetation Transpiration**: Upward heat flux from the surface.

- **Heat Release by Materials**: Heat released by human activities.

- **Heat Storage in Materials**: Heat released by human activities.

- **Upward Heat Flux from the Surface**: Represents the flow of heat from the surface in both directions.
URBAN CANOPY ENERGY BALANCE

\[ Q^* + Q_F = Q_H + Q_E + ΔQ_S + ΔQ_A \]

- Net radiation
- Anthrop. heat flux
- Sensible heat flux
- Latent heat flux
- Storage heat flux
- Net heat advection
Physical processes: example

the 4th of July, 2004

→ Anticyclonic situation
→ Warm temperatures (up to 34°C)
→ Very different rural/urban forcing:

![Graphs showing fluxes in City center and Countryside](image-url)
Observations and experiments
Canopy and Aerosol Particles Interaction in Toulouse Urban Layer (CAPITOUL) experiment

Toulouse
500,000 inhabitants
Old European city, brick and tiles
« Far » from the sea and mountains
Objectives

1) Energetic exchanges between city and atmosphere
2) The impact of the city on the atmosphere
3) The urban aerosol
4) Infra-Red Teledetection of the surface

→ All these experimental objectives are linked with modelling objectives
« CAPITOUL » experimental network

Stations météo complètes : température, humidité, vent, pression, pluie, bilan d'énergie

Mesure de vent par télédétection

aérosols

21 stations météo légères : température, humidité

Avion météo

Mat central : bilan d'énergie

Radio sondage

21 stations météo légères : température, humidité

Avion météo
Measurements of energy exchanges
Anthropogenic Heat

This is the main source of energy in winter

Net radiation

Observations from the instrumented tower
Estimation of anthropogenic heat over Toulouse, summer/winter
Inventory of $Q_F$ for the city center

- seasonal cycle for gas and electricity
- cycle linked to human activities for electricity and traffic
Modelling
Processes taken into account in the SURFEX model for a complex urban landscape:

**ATMOSPHERE**
- Temp, hum, wind

**RAIN**
- Snow
- Water

**VEGETATION**
- Temp, water, snow

**AIR IN THE STREET**
- Temp, hum, wind
- Air cond. & heating releases

**BUILDING**
- Wall
- Roof
- Temp, water, snow
- Shading
- Reflections
- IR exchanges

**AIR**
- Temp, water, snow

**ROAD**
- Temp, water, snow
- IR emissions

**GROUND**
- Temp, water

**Traffic - Industries**
- Emissions
- Heat
- CO$_2$

**On going implementation:**
- Direct radiation through windows
- Air conditioning releases
- Vegetation in the street
- Road orientation
- Ground water infiltration
- CO$_2$ emissions

**Processes taken into account**:
- Convection
- Conduction
- Radiation
- Evaporation
- Transpiration
- Infiltration
- Runoff
- Direct radiations
- Reflections
- IR exchanges
1) TEB (Town Energy Balance)

- Only 1 road, 1 roof, and 2 identical facing walls
  - ONLY ONE WALL SEB
  - Only one wall temp.
  - Only one road temp.

- Rain and snow interception
- Latent heat fluxes
- Heat conduction in the materials
- Anthropogenic fluxes
There is an important effort of measurements of urban surface energy balance & climate in the world

→ To understand urban climate

→ To validate models: here are presented the sites on which TEB has been validated
TEB has been validated against several dense urban sites:


*These validations allowed ameliorations* of the initial parameterizations of sensible heat exchanges in the canyon.
Domestic heating computed implicitly with a minimum internal temperature of 19°C. Internal temperature has its own equation evolution, not based on energy balance.

Focus on fall and winter periods during which heating is strong in Toulouse.

Use of observations collected during the CAPITOUL field campaign in Toulouse at a dense urban site.
The surface temperature measurements (Evaluation)

Rue Remusat
H/W 1.68, NE-SW

Rue Alsace-Lorraine
H/W 1.46, N-S

Rue Pomme
H/W 2.05, NW-SE

Roofs
(use of only 1)
Fall results: scatterplots of model vs obs.

- **NET RADIATION**
  - TEB
  - TEB & SBL

- **SENSIBLE HEAT**
  - TEB
  - TEB & SBL

- **ANTHROPOGENIC HEAT**
  - TEB
  - TEB & SBL

- **WALL TEMPERATURE**
  - TEB
  - TEB & SBL

- **ROAD TEMPERATURE**
  - TEB
  - TEB & SBL

- **ROOF TEMPERATURE**
  - TEB
  - TEB & SBL

Correct building surface temperatures
Winter results: scatterplots of model vs obs.

Correct building surface temperatures
Evaluation of TEB in cold and snowy conditions for the Montréal Urban Snow Experiment (MUSE) 2005

Aude Lemonsu¹, Stéphane Bélair², Jocelyn Mailhot², Sylvie Leroyer³

¹ Météo France/CNRS, GAME
² Environment Canada, Meteorological Research Division
³ Atmospheric and Environmental Research Lab, Mc Gill University
MUSE 2005 aimed at documenting the evolution of surface characteristics and energy budgets in a dense urban area during the winter-spring transition, with evolution of snow cover from ~100% to 0%

**Continuous measurements** (17 March – 14 April 2005)
- Radiation components: $K_\downarrow$, $L_\downarrow$, $K_\uparrow$, $L_\uparrow$
- Turbulent fluxes: $Q_H$, $Q_E$
- Surface temperatures of urban facets
- Air temperature in street and alley
- Snow depth on roof

**Manual measurements** (4 IOPs)
- Surface temperatures of urban facets
- Photographs
- Snow properties: $d$, $\rho$, $\alpha$, $T_S$

Lemonsu et al., JAMC, 2008: ‘Overview and first results of the Montreal Urban Snow Experiment (MUSE) 2005’
Montreal: urban snow measurements
17 March to 14 April 2005

Air temperature and humidity in canyons
Radiative temperature of walls

20 m tower

Radiative surface temperatures
IR camera in heated case
Incoming and outgoing radiation
CNR1 radiometer Kipp & Zonen

Turbulent fluxes by eddy covariance
10Hz
3D sonic anemometer CSAT3
H₂O/CO₂ analyzer Li-Cor 7500
Fine wire thermocouple ASPTC
Intensive observation periods

- Clear skies and southwest winds
- Four 26-hour IOPs (March 17-18, 22-23, 30-31, April 5-6)
- Measurements:
  - Hourly radiative surface temperatures using IR thermometer
  - Albedo (5 daytime measurements)
  - Snow depth and density (5 daytime measurements)
  - Pictures to document snow cover, snow melt, wet fraction

**Evolution of snow cover**

<table>
<thead>
<tr>
<th>March 17(^{th})</th>
<th>March 22(^{nd})</th>
<th>March 30(^{th})</th>
<th>April 5(^{th})</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image] 100 %</td>
<td>![Image] 95 %</td>
<td>![Image] 50 %</td>
<td>![Image] 10 %</td>
</tr>
</tbody>
</table>

100 % 95 % 50 % 10 %
URBAN CANOPY ENERGY BALANCE

\[ Q^* + Q_F = Q_H + Q_E + \Delta Q_S + Q_M + \Delta Q_A \]

- **Net radiation**
- **Anthrop. heat flux**
- **Sensible heat flux**
- **Latent heat flux**
- **Storage heat flux**
- **Snow melt flux**
- **Net heat advection**
URBAN CANOPY ENERGY BALANCE

\[ Q^* + Q_F = Q_H + Q_E + \Delta Q_S + Q_M - \Delta Q_A \]

- **Net radiation** (Measured)
- **Anthrop. heat flux** (Measured)
- **Sensible heat flux** (Measured)
- **Latent heat flux** (Measured)
- **Storage heat flux**
- **Snow melt flux**
- **Net heat advection** (Neglected)

(see Lemonsu et al. 2008)
Q_F diagnosed as the heat flux produced by domestic heating to maintain a comfort temperature inside buildings [Pigeon et al. 2008]

Q_F estimated using data of electricity consumption provided by Hydro-Quebec

Q_F found to be negligible in comparison with the other fluxes.
Energy budget correctly simulated by TEB-ISBA with snow

Melting is a predominant term of the budget (27 %)

\[
Q_{\text{res}} \approx \Delta Q_S + Q_M - Q_F
\]

- Storage heat flux
- Snow melt flux
- Anthrop. heat flux
Examples of Applications
Urban heat Island

Lemonsu and Masson (2002), CNRM, Toulouse, France

3D Simulation over Paris
With the Meso-NH atmospheric model coupled with TEB

- UHI maximum at night (positive heat flux)
- Small UHI at day
Urban breeze over Paris

With urban parameterization (TEB)

- City is warmer
- Urban breeze develops
- Winds strongest over suburban area

⇒ Effect of heat dominates over roughness

Without urban parameterization

Nothing happens

Lemonsu and Masson (2002)
Analysis of the transformations of Nantes city from 17th to 20th century:

- Ground cover, density, deviation of rivers,...
- Building type, urban design, insulation...
- Usages: sewers, domestic heating,...

Source: Benzerzour 2004
Urban micro-climate impacts are simulated with TEB:

- Wind decrease up to the middle of the 19th century (densification, increase of number of stories)
- Wind increase after (larger roads)
- Increase of 1,5°C between the 17th and the 20th century
- Slight decrease of humidity
In SURFEX
Options & Namelists

- There is very few scientific options in TEB (for the time being…)

- In ‘PGD’ step:
  - Nothing to do if ecoclimap is used
  - Possibility to specify all urban characteristics in Namelist NAM_DATA_TEB
## Input data for TEB-SURFEX

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Atmosphere</strong></td>
<td></td>
</tr>
<tr>
<td>Air temperature above canopy</td>
<td>K</td>
</tr>
<tr>
<td>Specific humidity above canopy</td>
<td>kg kg⁻¹</td>
</tr>
<tr>
<td>Incoming solar radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Infrared solar radiation</td>
<td>W m⁻²</td>
</tr>
<tr>
<td>Air pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>Rainfall rate</td>
<td>kg m⁻² s⁻¹</td>
</tr>
<tr>
<td>Snowfall rate</td>
<td>kg m⁻² s⁻¹</td>
</tr>
<tr>
<td>Wind speed</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>Wind direction</td>
<td>deg / North</td>
</tr>
<tr>
<td>Carbon dioxyde concentration</td>
<td>kg m⁻³</td>
</tr>
<tr>
<td><strong>Land Use</strong></td>
<td></td>
</tr>
<tr>
<td>Urban area fraction</td>
<td>-</td>
</tr>
<tr>
<td>Nature area fraction</td>
<td>-</td>
</tr>
<tr>
<td>Sea area fraction</td>
<td>-</td>
</tr>
<tr>
<td>Lake area fraction</td>
<td>-</td>
</tr>
</tbody>
</table>
# Input data for TEB-SURFEX

| Urban morphology and building thermal and radiative characteristics | Building area fraction (inside urban fraction) | - |
| | Road area fraction (inside urban fraction) | - |
| | Wall surface / building and road surface | - |
| | Building height | m |
| | Urban roughness length | m |
| | Number of wall layer | - |
| | Number of roof layer | - |
| | Number of road layer | - |
| | Wall layers depth | m |
| | Roof layers depth | m |
| | Road layers depth | m |
| | Wall layers specific heat | J m$^{-3}$ K$^{-1}$ |
| | Roof layers specific heat | J m$^{-3}$ K$^{-1}$ |
| | Road layers specific heat | J m$^{-3}$ K$^{-1}$ |
| | Wall layers thermal conductivity | W m$^{-1}$ K$^{-1}$ |
| | Roof layers thermal conductivity | W m$^{-1}$ K$^{-1}$ |
| | Road layers thermal conductivity | W m$^{-1}$ K$^{-1}$ |
| | Roof albedo | - |
| | Road albedo | - |
| | Wall albedo | - |
| | Roof emissivity | - |
| | Road emissivity | - |
| | Wall emissivity | - |

| Anthropogenic heat releases | Anthropogenic sensible and latent heat flux released by traffic | W m$^{-2}$ |
| | Anthropogenic sensible and latent heat flux released by industry | W m$^{-2}$ |

| Vegetation | Area fraction of bare soil | - |
| | Area fraction of low vegetation | - |
| | Area fraction of high vegetation | - |
| | Leaf Area Index (for each veg. Type and month) | - |
| | Vegetation roughness length (for each veg. type and month) | - |
| | Vegetation characteristics for photosynthesis and vegetation growing (for each veg. type) | m |
Options & Namelists

- There is very few scientific options in TEB (for the time being…)

- In ‘PGD’ step :
  - Nothing to do if ecoclimap is used
  - Possibility to specify all urban characteristics in Namelist NAM_DATA_TEB

- In ‘PREP’ step : Namelist NAM_PREP_TEB :
  - Initializes the surface temperatures, water reservoirs and snow
  - Possibility to activate the SBL (or « canopy ») scheme

- During the run : Namelist NAM_TEBn
  - Only one option (thanks to Canadian developers) : choice of the thermal roughness length for roofs and roads : CZ0H

- Several diagnostics in Namelist NAM_DIAG_TEBn
Conclusions

- Most important characteristics of urban surface energy exchanges well reproduced by TEB:
  - Upward radiative fluxes (trapping, …)
  - Building surface temperature
  - Strong contribution of $Q_H$ during the day
  - Small positive $Q_H$ values during the night
    (thanks to energy storage during the day)
  - High values of the anthropogenic heat flux in winter
  - Snow mantel evolution & snow melt

- TEB allows both offline applications on urban impacts and online atmospheric simulations of urban climate and meteorology (e.g. UHI)
Perspectives

- Better inside building energy balance & Including direct heat releases from building through chimneys
- Including heat releases due to air conditioning
- Add vegetation into TEB, to allow human comfort studies
- Use of TEB for the forecast of the energy demand for thermal comfort in buildings at the scale of a city and with different climate change scenarios