The Town Energy Balance (TEB): An urban surface parametrisation developed at Météo France

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Outline

- Motivation for the development of the Town Energy Balance (TEB)
- Fundamentals of TEB
- Meteorological forcing data
- Applications for urban climate studies
- The CAPITOUL campaign and TEB tutorial

Motivation for the development of the Town Energy Balance (TEB)

Surface energy, water and momentum balance depends on land use type

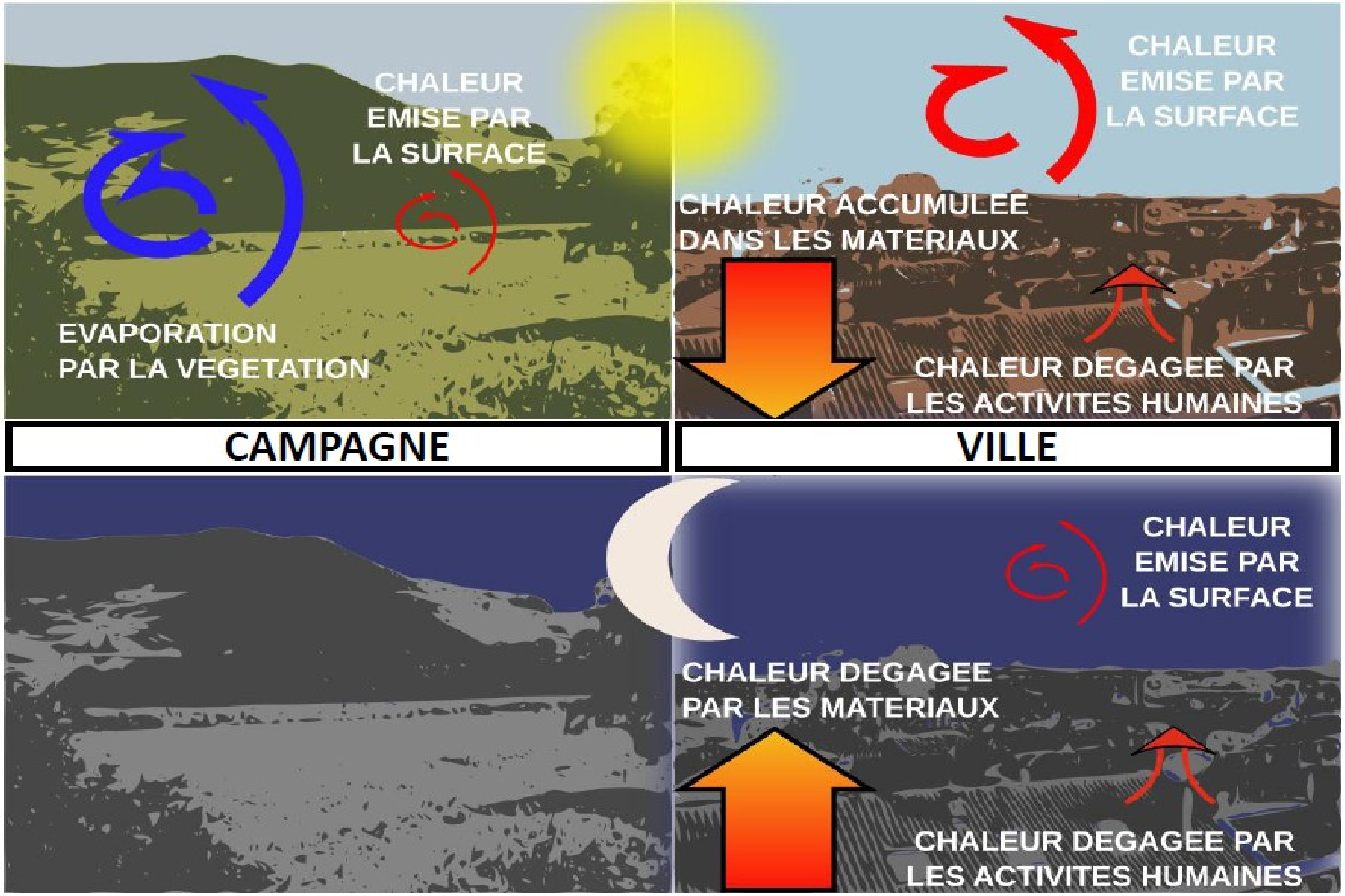
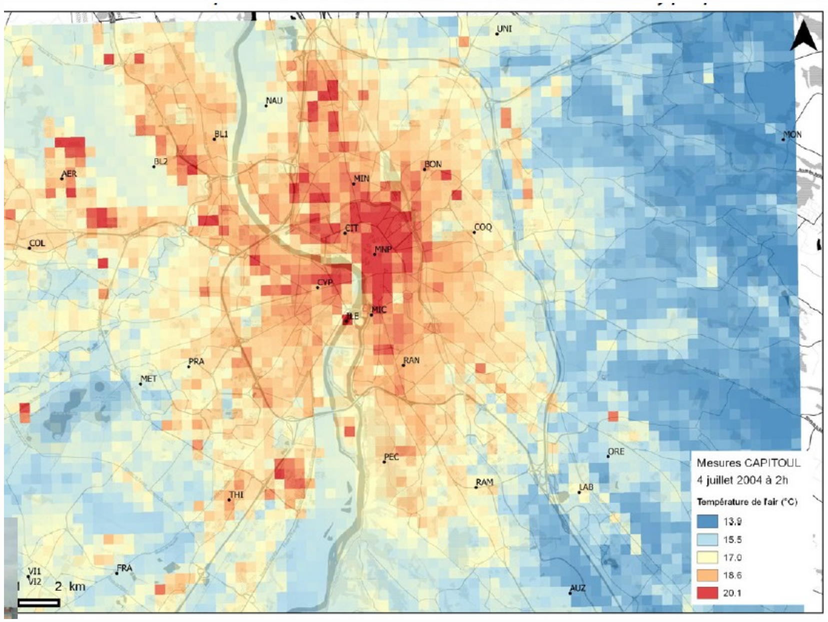


Figure: De Munck (2013)

Surface energy balance impacts local climate

Differences between urban and rural climate

- (Nocturnal) air temperature higher in urban area (UHI)
- Relative humidity lower in urban area
- Absolute humidity can be higher in urban area
- Wind speed lower in urban area
- Enhancement/suppression of clouds and precipitation possible



Nocturnal (2 a.m.) air temperature observed in Toulouse on July 4 2004 during the CAPITOUL campaign (Masson et al., 2008)

SURFEX: A surface parametrisation for atmospheric models

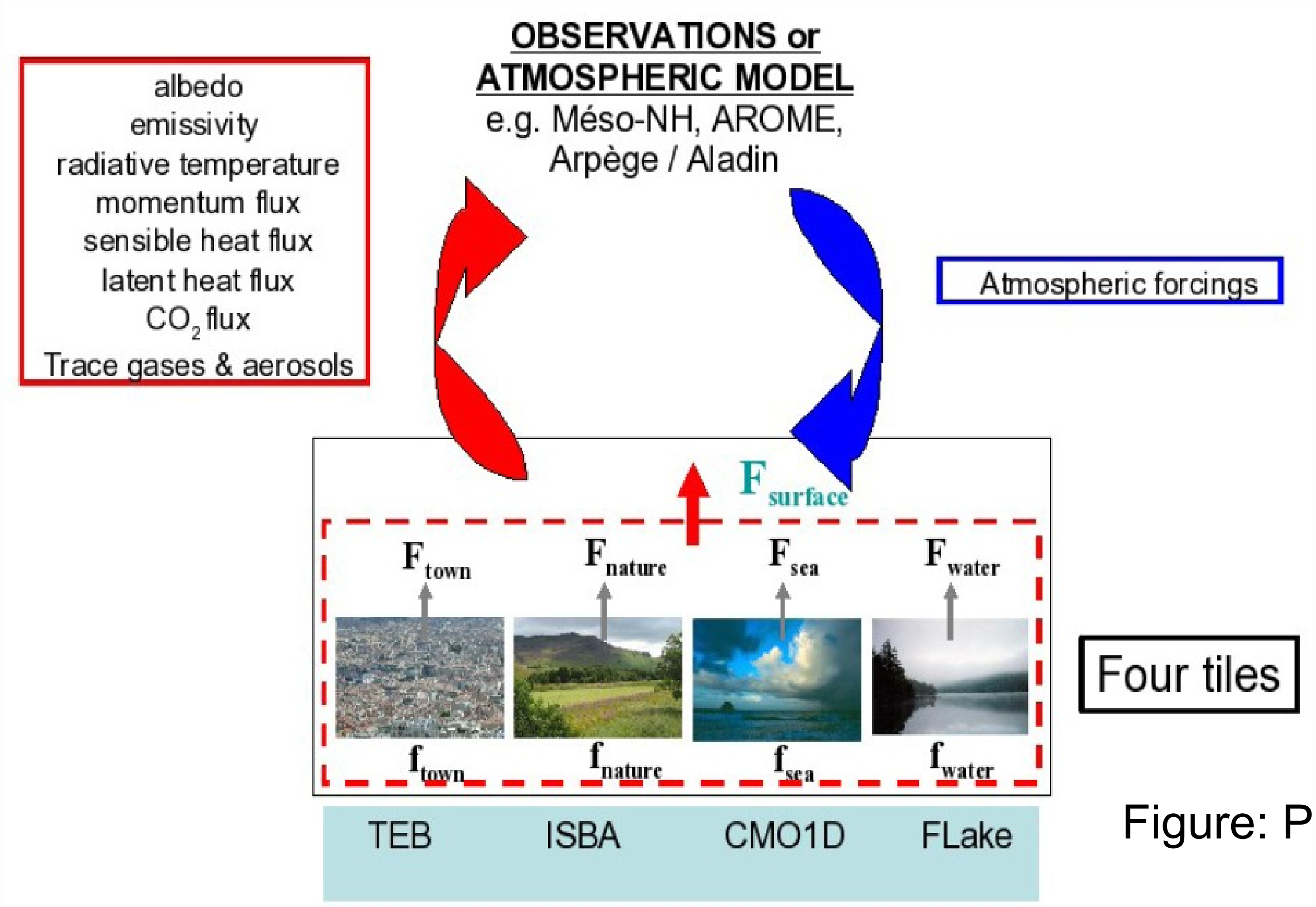


Figure: Pigeon (2009)

What is TEB made for?

Purpose and design of TEB

- Urban surface energy, water, momentum balance for atmospheric models
- Sensible and latent heat flux, momentum and radiation exchange
- The scale of application is an urban district, not single buildings
- Numerical integration must be a lot faster than for atmospheric model

TEB is not designed for

- Simulations at the scale of one single building
- Details of the wind and temperature fields in the street canyons
- Details inside the buildings

Fundamentals of TEB

TEBs assumptions on urban morphology

- **Buildings oriented along street canyons with length >> width**
- **Homogeneous urban morphology**
  - Buildings in one district have the same height
  - Street canyons in one district have the same width
- **Street canyon orientation can be taken into account**
- **Single layer urban canopy model (one-node walls, ...)**

Radiation modification due to buildings

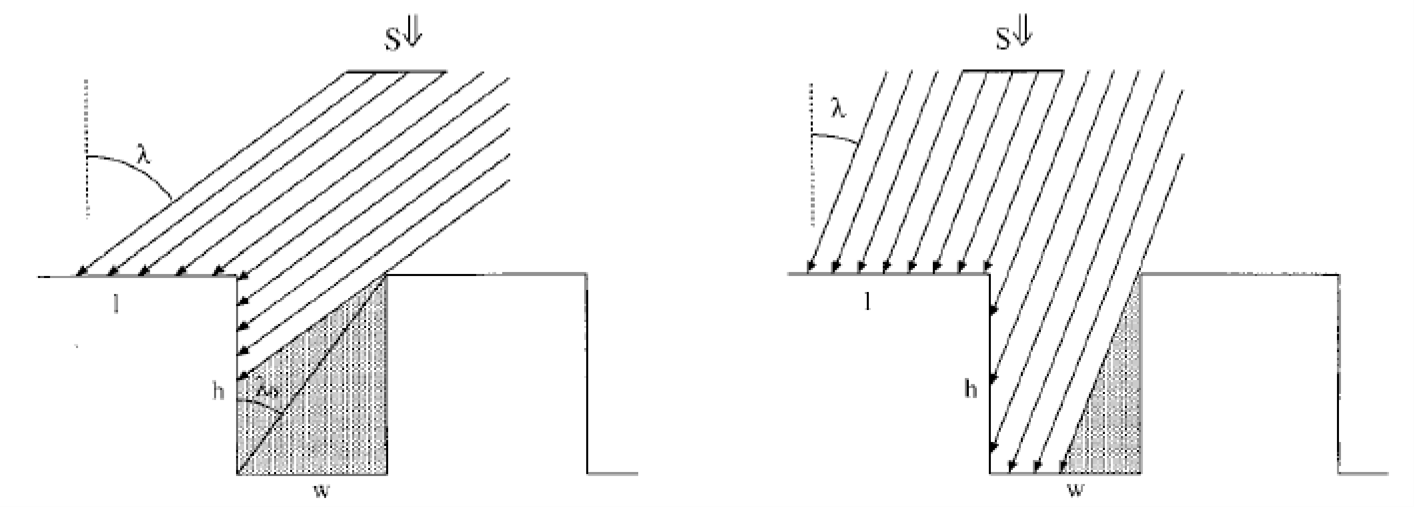


Figure: Masson (2000)

Only **average** shortwave and longwave radiation on roof, road, insolated and shaded wall

Only **one value** for the surface temperatures

Calculation of temperature, humidity and wind speed inside the street canyon

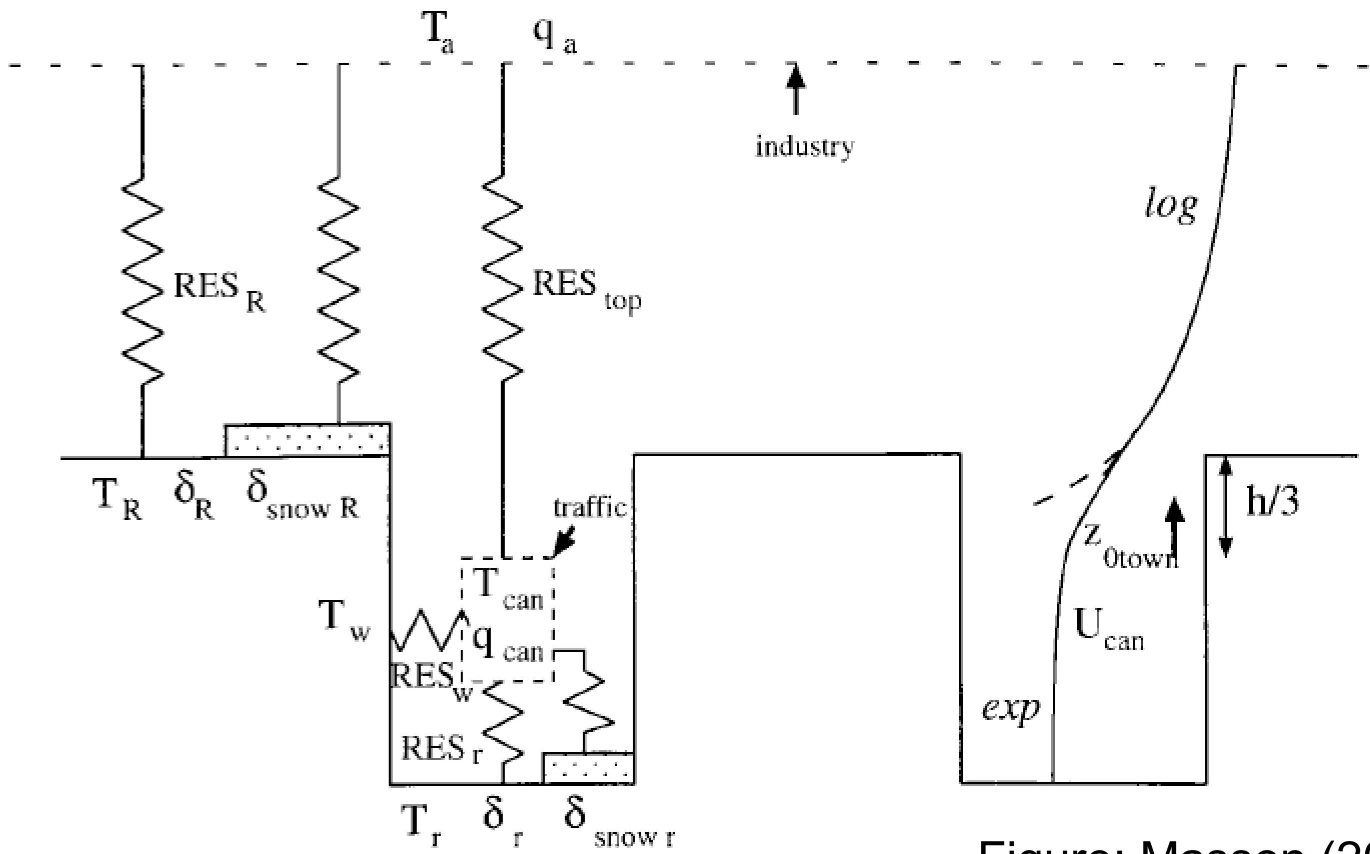


Figure: Masson (2000)

Canopy option in more recent code versions

BEM: A Building Energy Model for TEB

- **Why a building energy model for TEB?**
  - Indoor air temperature influences HVAC energy demand
  - HVAC demand can be major part of anthropogenic heat flux
  - This can have important implications for urban climate (mainly UHI)

- **BEM: Building Energy Model (Bueno et al., 2012)**
  - One-node building model integrated in TEB
  - Same assumptions for morphology than for TEB

The TEB-BEM approach allows for a simulation of the interactions between urban climate and HVAC energy demand

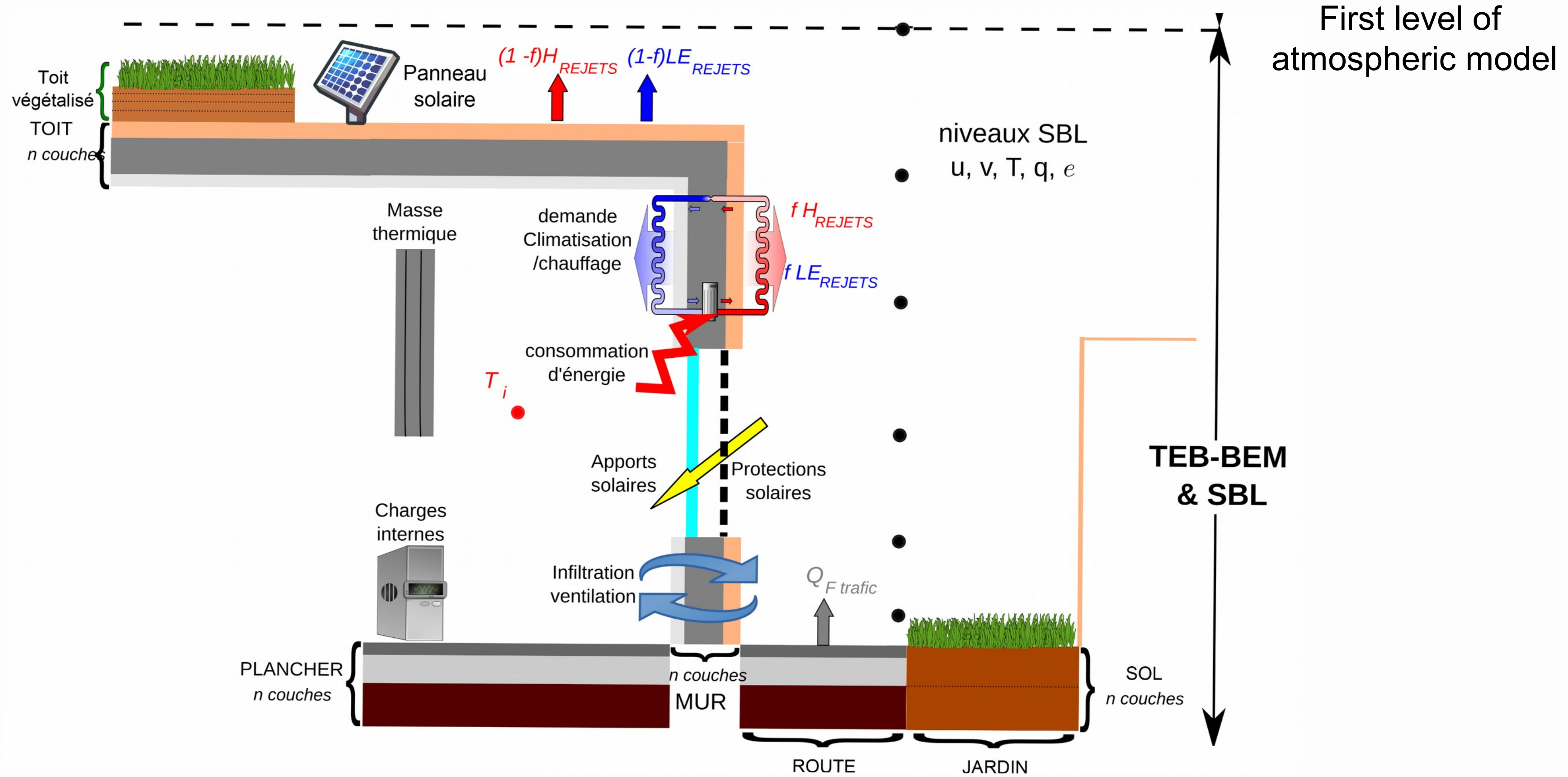
Main interactions between urban climate and building energy demand

- **Meteorological conditions in the city influence**
  - Heating and cooling energy demand
  - Ventilation and shading by building occupants
  - Use of lighting devices by building occupants

- **Building energy demand leads to**
  - Increase of anthropogenic sensible and/or latent heat
  - Amplification of (nocturnal) urban heat island (UHI)

- **Feedbacks between UHI and building energy demand**
  - Negative during heating season
  - Positive during cooling season

Scheme of TEB-BEM (thanks to Julien Le Bras)



TEB: Masson (2000)
BEM: Bueno et al. (2012); Pigeon et al. (2014)
Garden: Lemonsu et al. (2012)
Greenroof: De Munck et al. (2013)

Prognostic and diagnostic variables

- **Main prognostic variables**
  - Roof, wall, road, mass and floor temperature (several layers)
  - Town sensible and latent heat flux
  - Town net solar and net infra-red radiation
  - Indoor air temperature and humidity
  - HVAC energy demand

- **Main diagnostic variables**
  - Street canyon air temperature and humidity
  - Along canyon horizontal wind speed
  - Town effective albedo
  - Town average radiative surface temperature

Evaluation and validation of TEB and BEM

- **Evaluation of TEB**
  - Dry version (Mexico City and Vancouver; Masson et al., 2002)
  - Including vegetation (Marseille; Lemonsu et al., 2004)
  - Fall and winter (Toulouse; Pigeon et al., 2008)
  - Including snow cover (Montreal; Lemonsu et al., 2010)
  - Further evaluations by TEB user community

- **Comparison between BEM and Energy+ (Pigeon et al., 2014)**
  - Five representative buildings in Paris
  - Heating and cooling demand within ~15%
  - Single-node building model seems “sufficiently good”

Required input data characterising the urban area

- **Surface cover fractions (building, road, vegetation, water)**
- **Urban geometry**
  - Building height
  - Street canyon orientation
  - Wall to horizontal area ratio
- **Architectural characteristics**
  - Albedo, emissivity, thickness, thermal conductivity and heat capacity of roofs, walls, road, floor and mass
  - Several layers with different materials can be dealt with
  - Window characteristics (U-Value, SHGC)
- **Behavioural characteristics**
  - Heating and cooling design temperature
  - Building internal heat release
  - Window and shading use

Meteorological forcing data

General specifications of meteorological forcing data

- **Required meteorological forcing data**
  - Air temperature and specific humidity
  - Wind speed and direction
  - Air pressure
  - Direct and diffuse downwelling solar radiation
  - Downwelling infra-red radiation
  - Rain and snow fall rate
- **Origin of forcing data**
  - Lowest level of atmospheric model (e.g. Méso-NH)
  - Observation based data (e.g. meteorological station)
  - The forcing must be consistent with the TEB formulation
- **Temporal resolution should be about 1 hour**

Requirements for forcing data

The forcing data for TEB-BEM must represent
the meteorological conditions
above the average building height
in the
urban boundary layer

- **The forcing data for urban areas must not be**
  - Rural station observations at 2 m
  - Rural station observations extrapolated to ~30 m
  - Urban station observations at 2 m
  - Output of atmospheric model at 2 m

Simple scheme of nocturnal urban and rural boundary layer

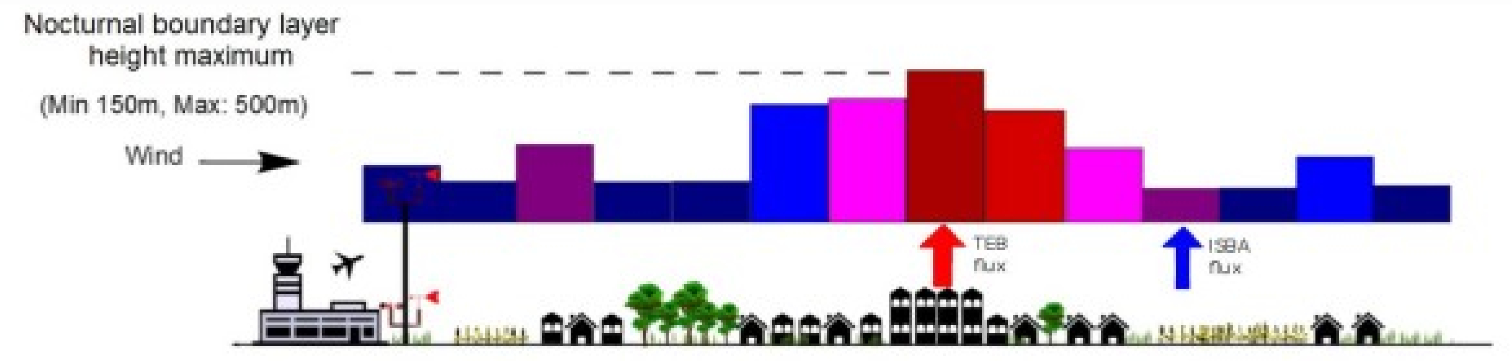


Figure: Le Bras and Masson (2015)

- **Use of rural data at 30 m as forcing for TEB leads to**
  - Neglection of potential UHI at 30 m
  - Underestimation of canyon air temperature by TEB
  - Town sensible heat flux might be too large
  - ….

The urban weather generator: A methodology for numerically cheap forcing of TEB with station data

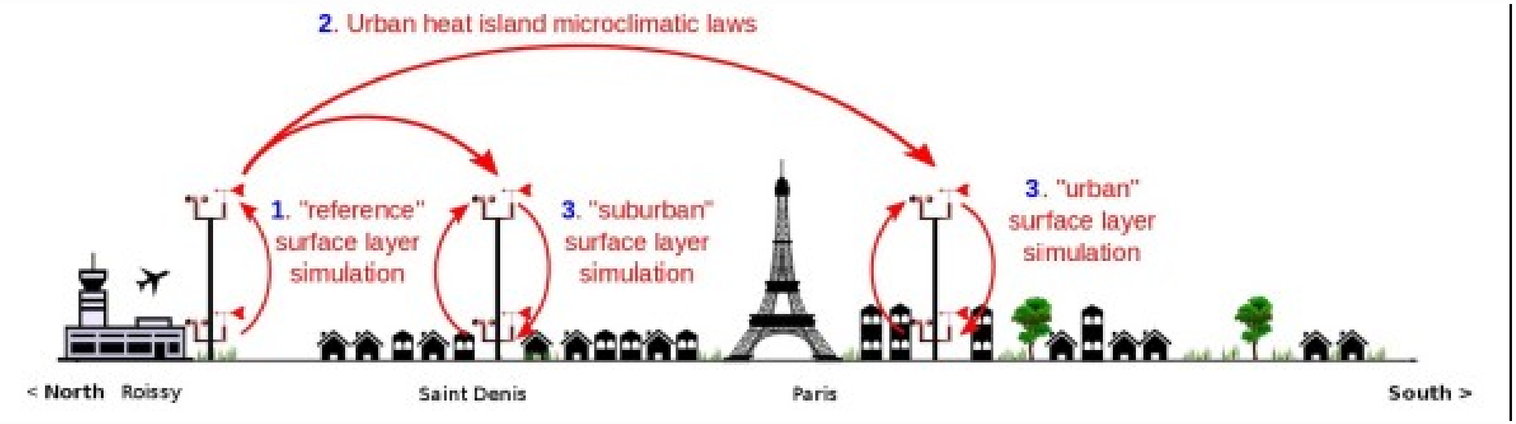


Figure: Le Bras and Masson (2015)

The urban weather generator (Bueno et al., 2013; Le Bras and Masson, 2015) is based on an energy balance of the urban boundary layer

It allows for urban climate simulations with TEB forced by station observations

Application of the urban weather generator for Paris

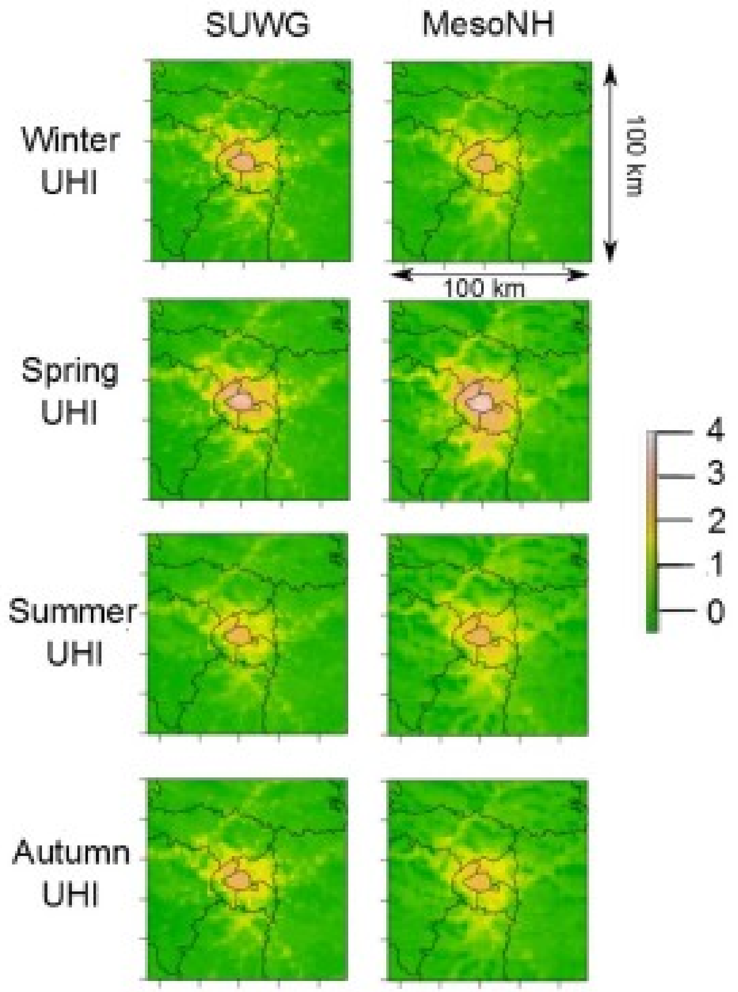


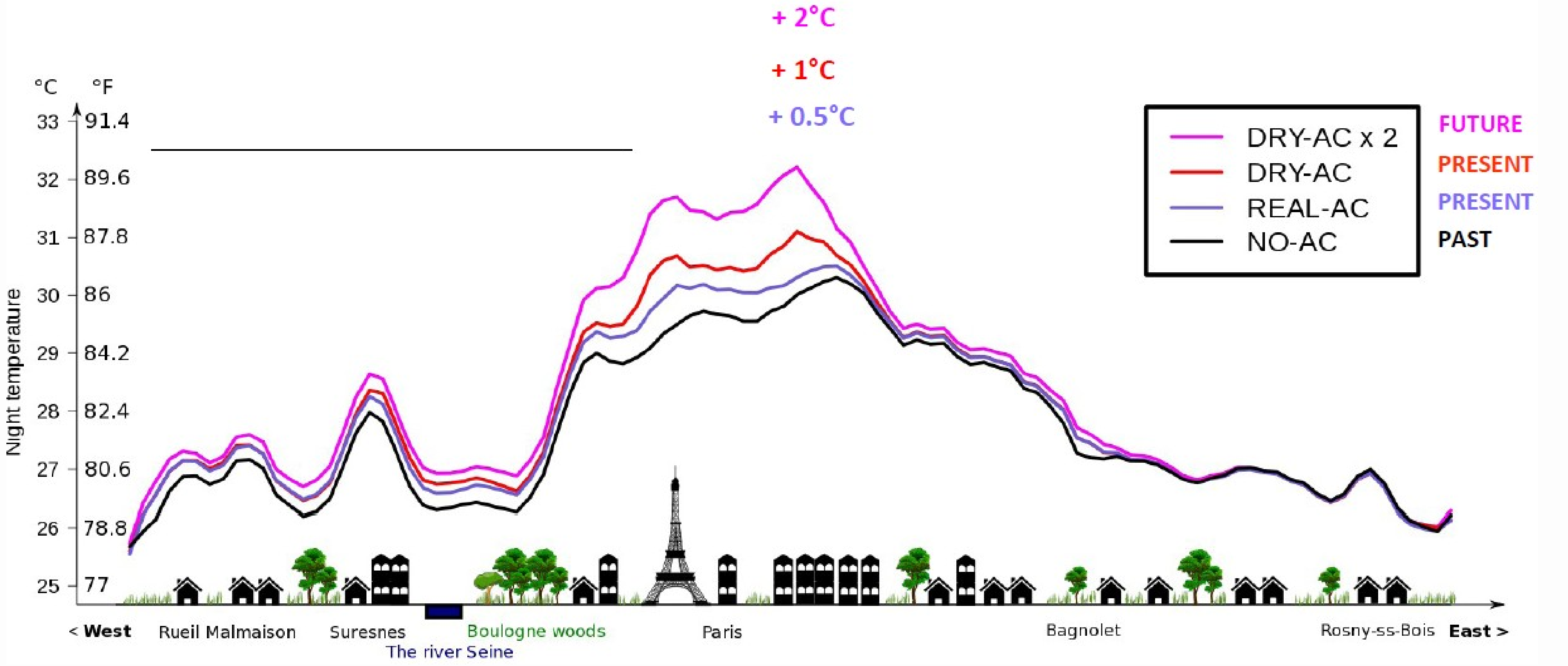
Figure: Le Bras and Masson (2015)

For Paris the urban weather generator compares well to Méso-NH

Larger biases might occur in the presence of hills or for cities close to the shore

Applications for urban climate studies

Impact of air conditioning on the UHI of Paris
Result of De Munck et al. (2013)



Impact of ground-based urban vegetation on canyon daily minimum air temperature (De Munck, 2013)

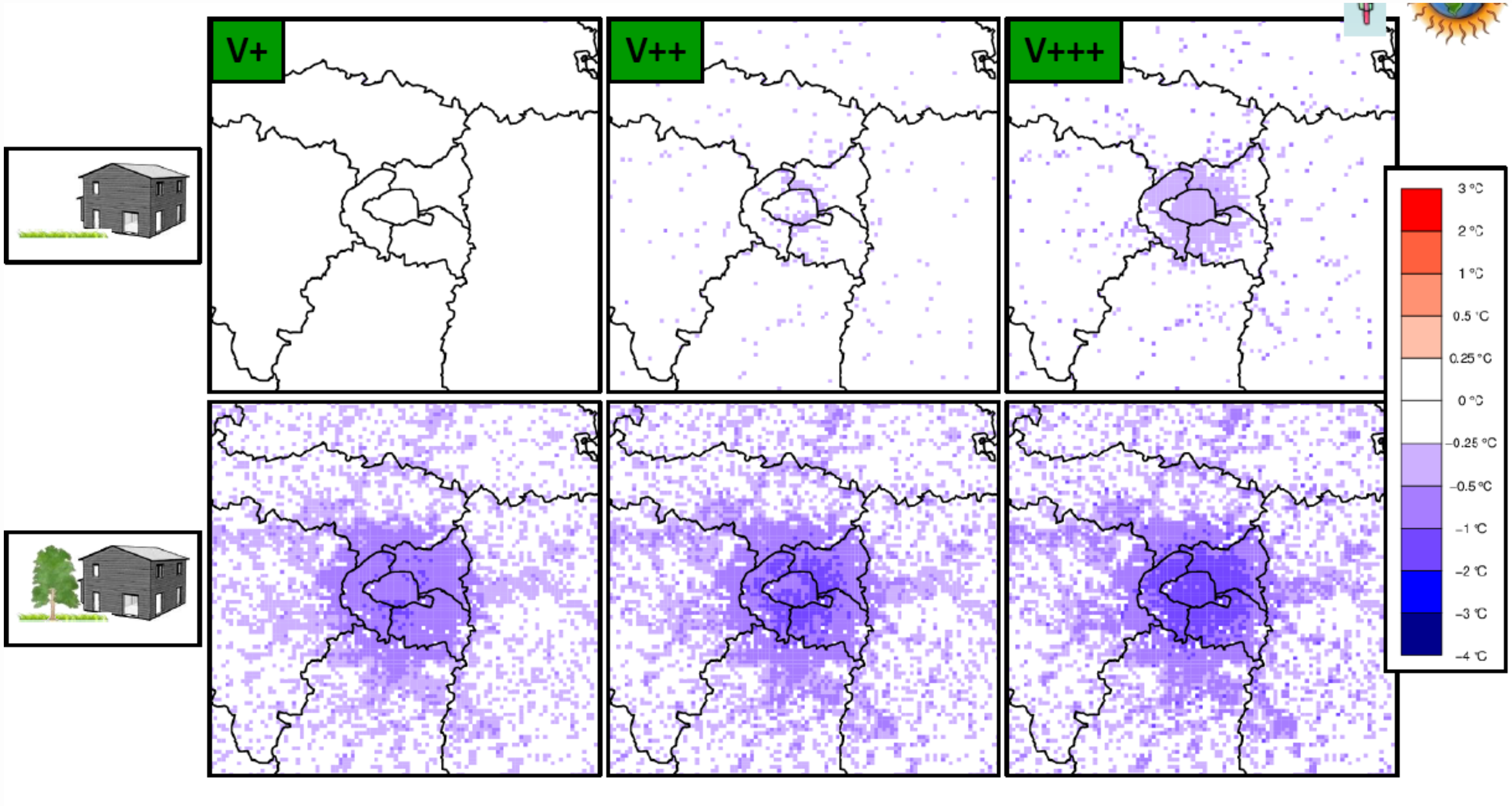


Figure: De Munck (2013)

Impact of green roofs on canyon daily maximum air temperature (De Munck, 2013)

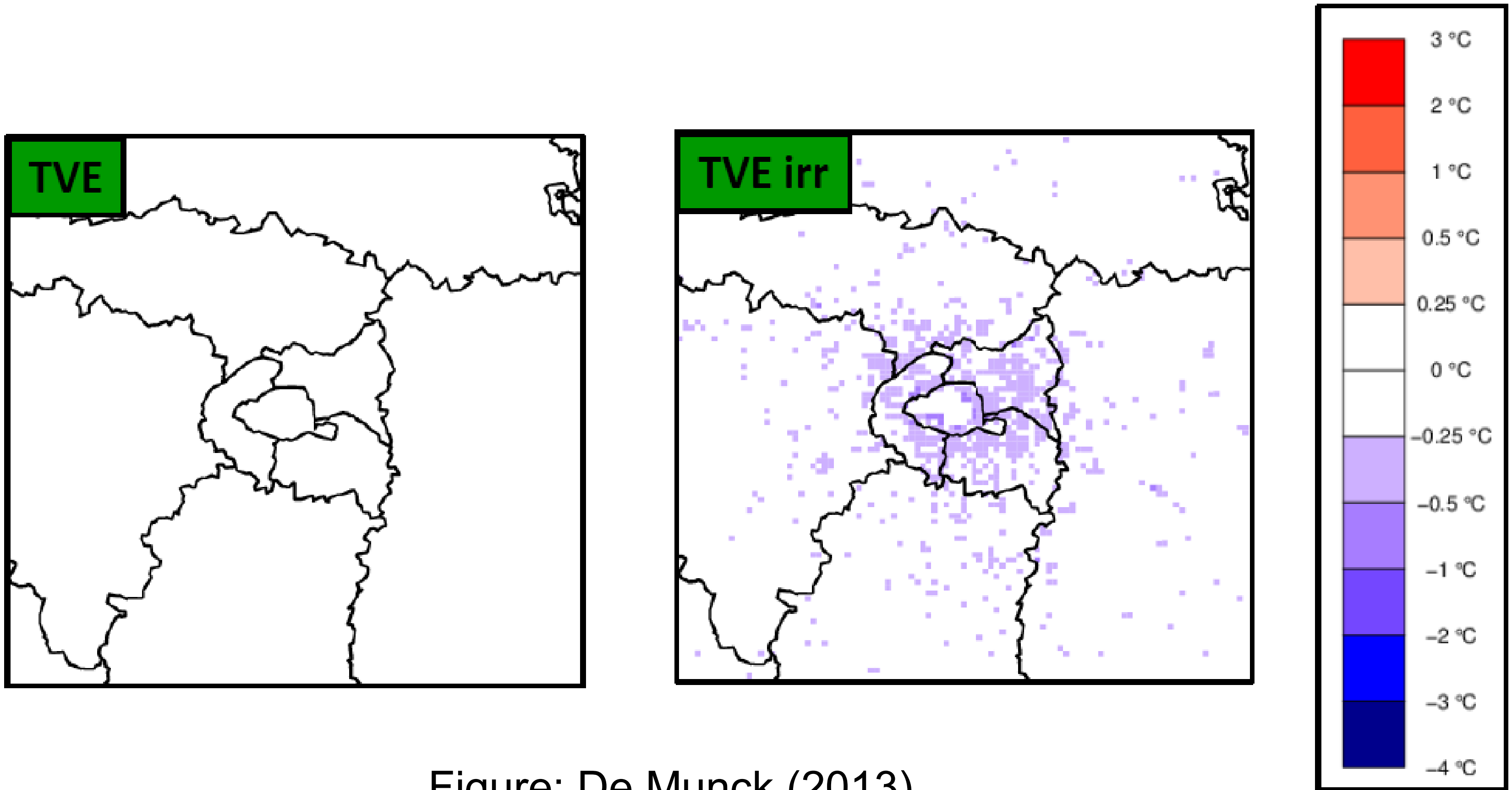
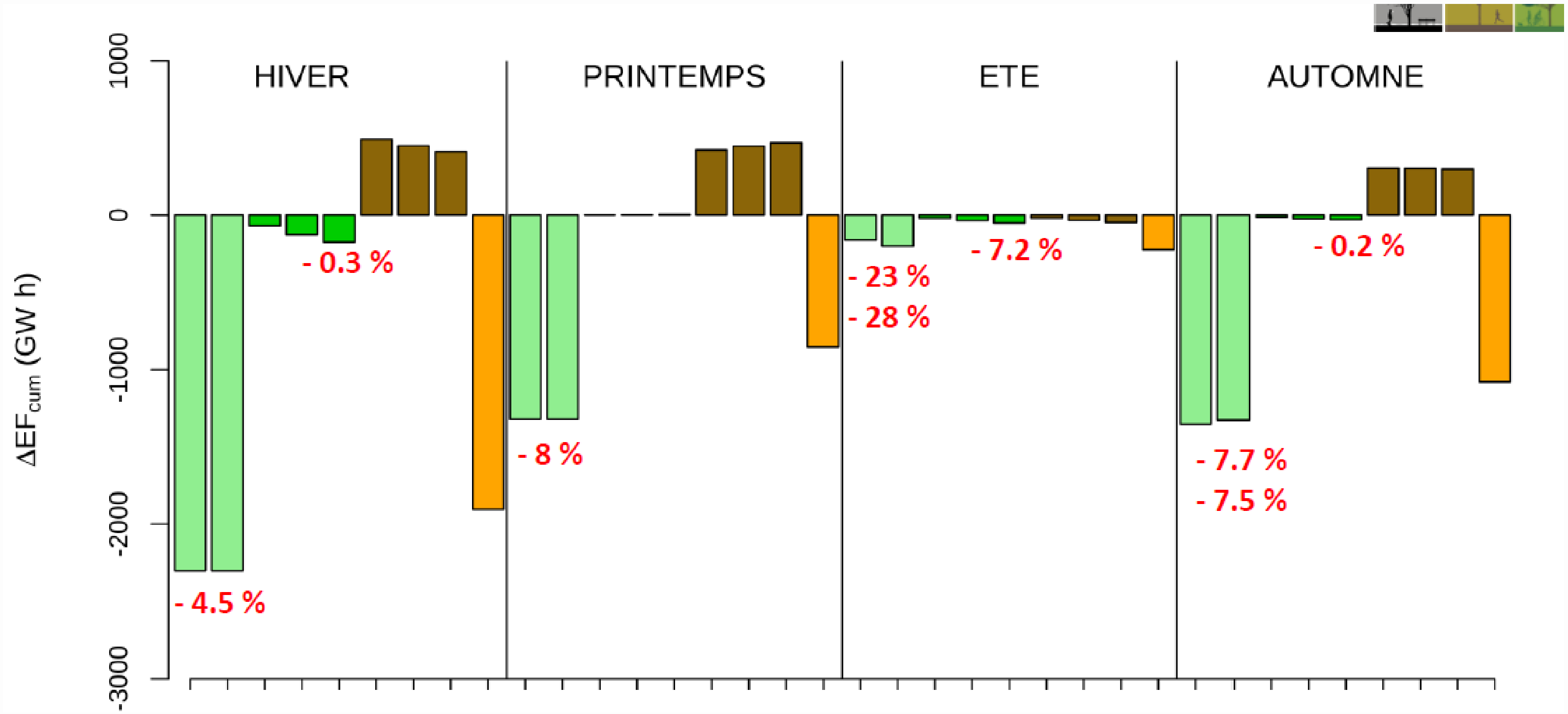


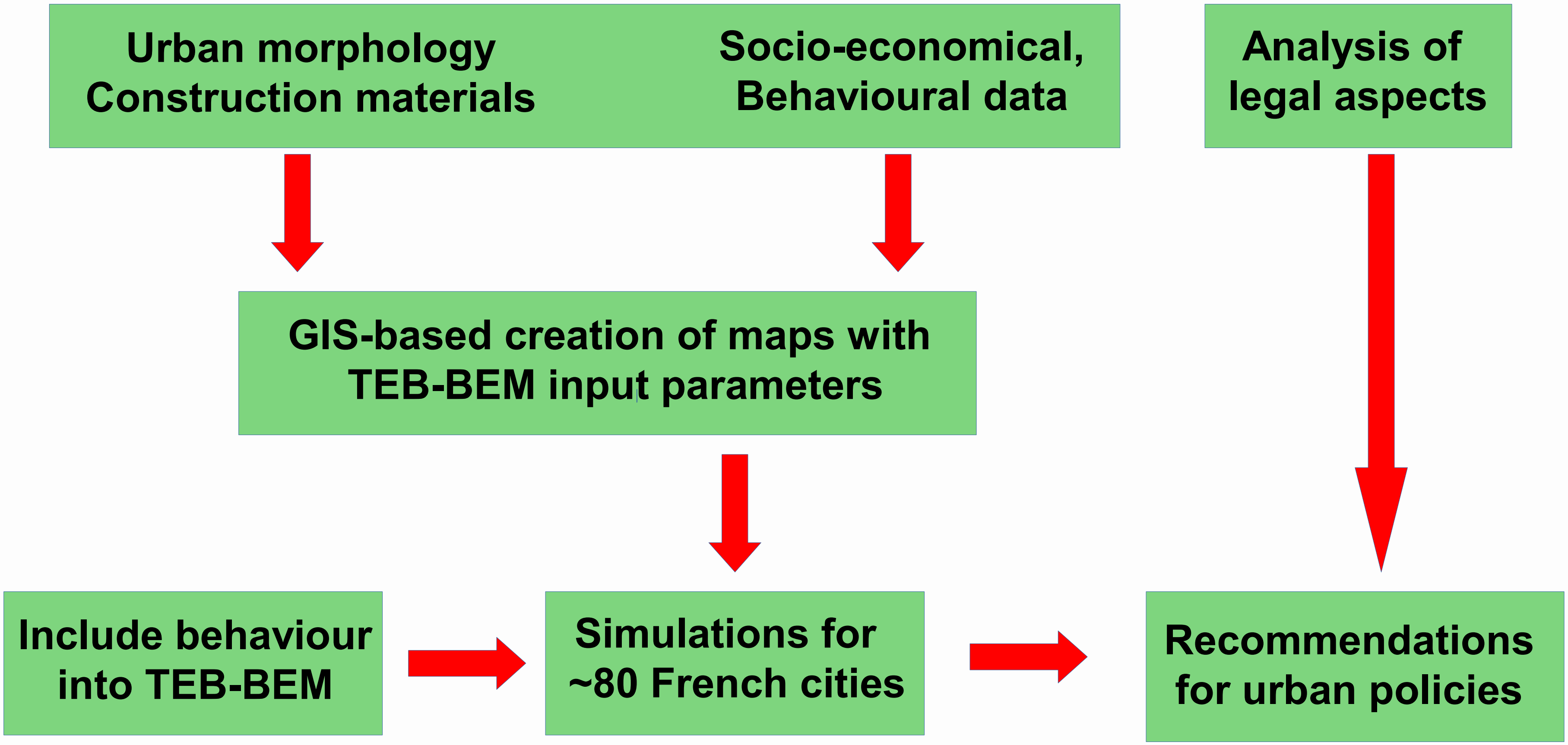
Figure: De Munck (2013)
TVE = Green Roof

Impact of greening on HVAC demand
Results of De Munck (2013)



Green roofs reduce HVAC demand in all seasons
Street trees increase heating energy demand
For summer all greening strategies reduce cooling energy demand

The ANR-MApUCE project: generation of quantitative data on coupled urban climate and energy consumption



The MApUCE project milestones

- **Creation of MapUCE database (~80 largest cities in France)**
  - Urban morphology and architectural data
  - Islet type, building age and usage
  - Data characterising human behaviour
  - Spatial resolution: islets = Unité Spatiale de Référence (USR)
- **Selection of urban climate simulation strategy**
  - SURFEX forced by Méso-NH
  - SURFEX forced by urban weather generator
  - Which complexity is required for which type of urban area?
- **Productive simulations for the ~80 largest cities in France**
  - Production of maps: urban climate and energy consumption
  - Some scenarios (adaptation measures, building regulations)

Building HVAC energy demand prediction might be possible based on MApUCE achievements

The CAPITOUL campaign and TEB tutorial

The CAPITOUL campaign

- **CAPITOUL (Masson et al., 2008)**
  - Observations in Toulouse, February 2004 to March 2005
  - Urban surface energy balance measured at meteorological mast
  - Various other observations (stations, airborne, …)

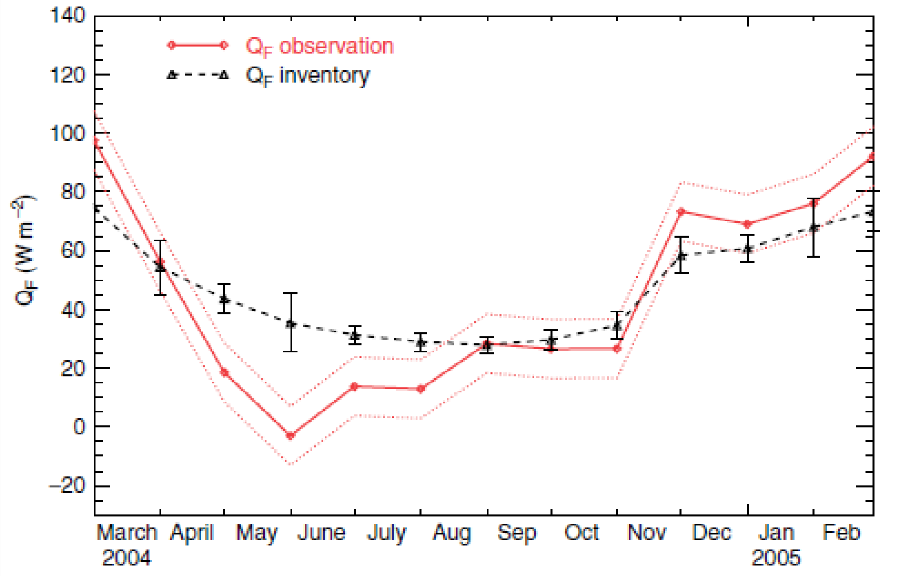
- **Centre of Toulouse**
  - Homogeneous urban morphology
  - ~20 m high red brick buildings
  - Vegetation is rare
  - Not much industry

CAPITOUL's anthropogenic heat release estimations

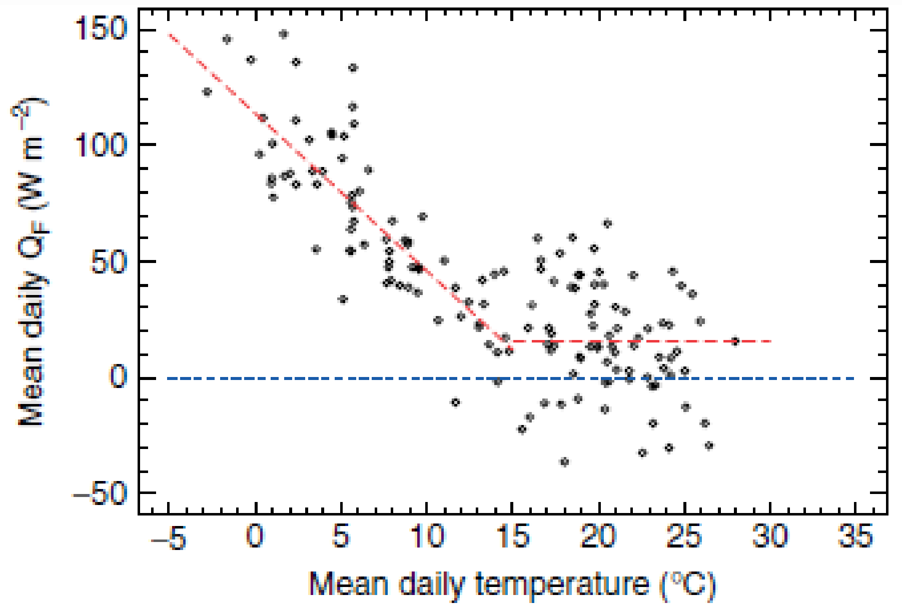
- **Meteorological mast observations**
  - Radiative fluxes
  - Sensible and latent heat fluxes
  - Anthropogenic heat release as residuum
  - Advection and storage introduce noise
  - Observed turbulent fluxes biased
  - Residuum is biased

- **Inventory of anthropogenic heat**
  - Traffic fuel, electricity, gas, domestic fuel, coal, wood
  - No biases due to meteorological noise
  - Spatial and temporal resolution limited by data availability

Anthropogenic heat release of Toulouse
Results of Pigeon et al. (2007)



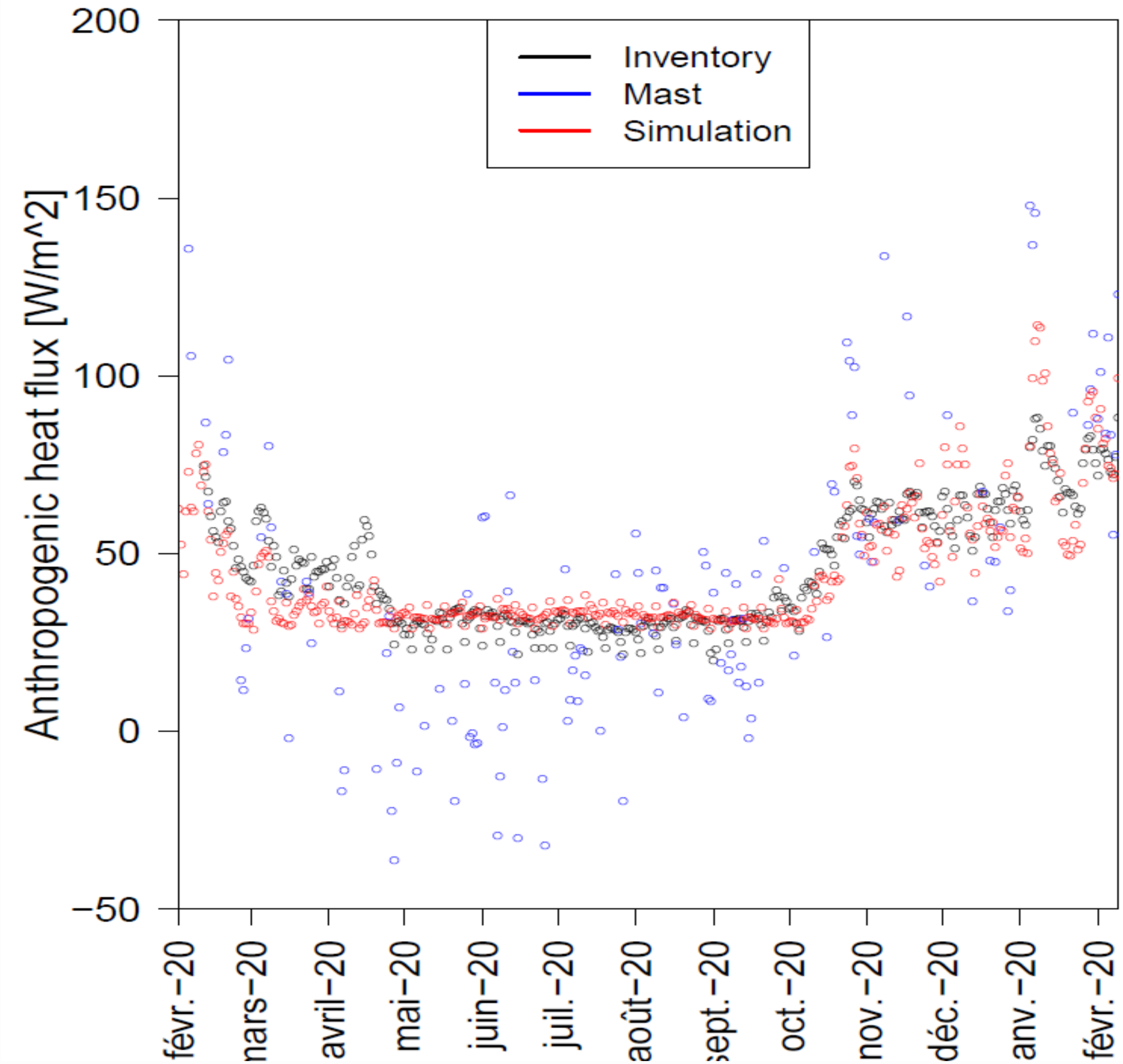
Largest difference in spring
Reason: bias of latent heat flux?



Very strong influence of heating
No effects of cooling
Noise!

CAPITOUL ideal for evaluation of MAPUCE results

Estimation of anthropogenic heat for CAPITOUL using TEB-BEM



Best results for 'reasonable' values of behavioural input parameters

Initialisation problem?
Too high a sensitivity!
August holidays?

Issues with different spatial representativities of mast, inventory and model

Options for download of SURFEX and TEB
The codes are written in Fortran90!

- **SURFEX (TEB+ISBA+FLAKE+CMO1D)**
  - http://www.cnrm.meteo.fr/surfex/
  - Essential scientific publications on TEB and ISBA
  - SURFEX scientific and technical documentation
  - A license agreement needs to be signed with Météo France

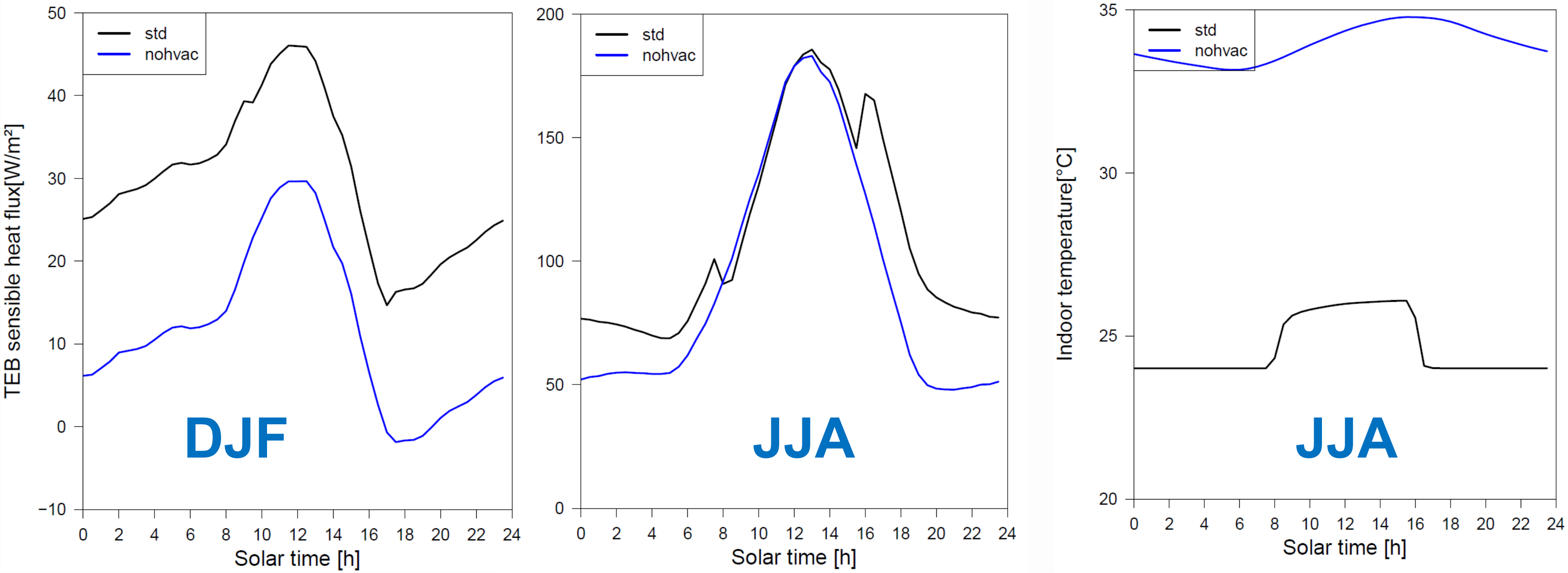
- **TEB-Opensource**
  - https://opensource.cnrm-game-meteo.fr/projects/teb/files
  - Contains a very simple vegetation model
  - Essential information in README.txt

Specification of TEB-Opensource

- **TEB-Opensource is hardcoded for CAPITOUL**
  - In **driver.F90**: input parameters for CAPITOUL
  - In **input** folder: CAPITOUL mast meteorological forcing (30 min.)
  - Compilation using **make**
  - Execution of compiled program: **./driver.exe**
  - Output (30 min.) can be found in **output** folder
  - Test your installation by comparing **output** and **output_ref**
  - Small differences (~10^-4) can be due to platform dependency

Prepared experiments
- Influence of heating and climatisation

- **“std”** (theat_target = 292.15 K; tcool_target = 297.15 K)
- **“nohvac”** (theat_target = 200 K; tcool_target = 400 K)

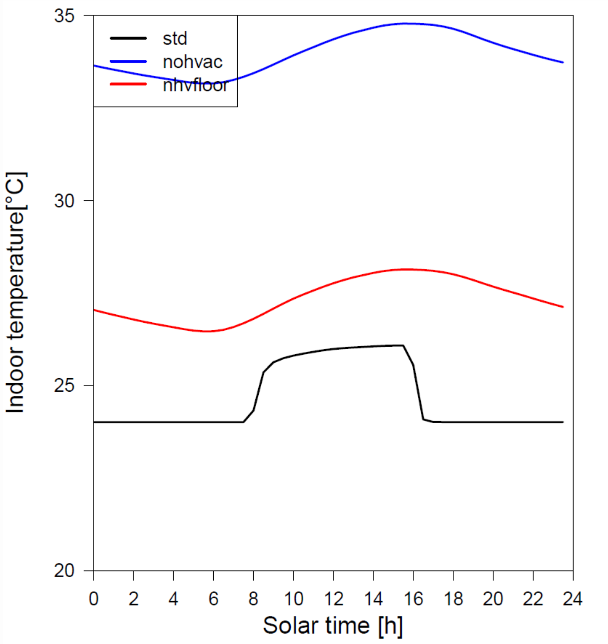


Heating has strong influence on town sensible heat flux during winter
Cooling has a strong impact during the night in the summer season

Without cooling: Unrealistic high values for indoor temperature during summer. This is due to the zero flux ground floor boundary condition at 25 cm depth

Prepared experiments
- Changed boundary condition for the deep floor

“nhvfloor” (deep floor temperature hardcoded to 19 °C)



Resolves problem of unrealistic indoor temperature

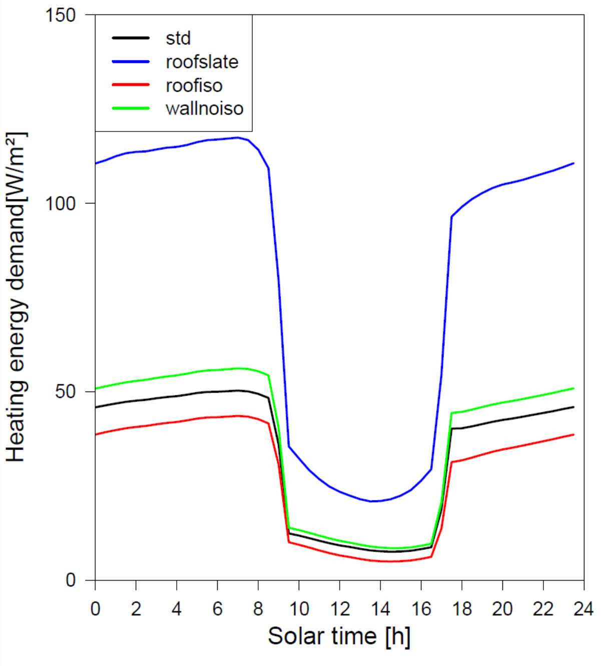
Problem:
- arbitrary
- violation of energy conservation

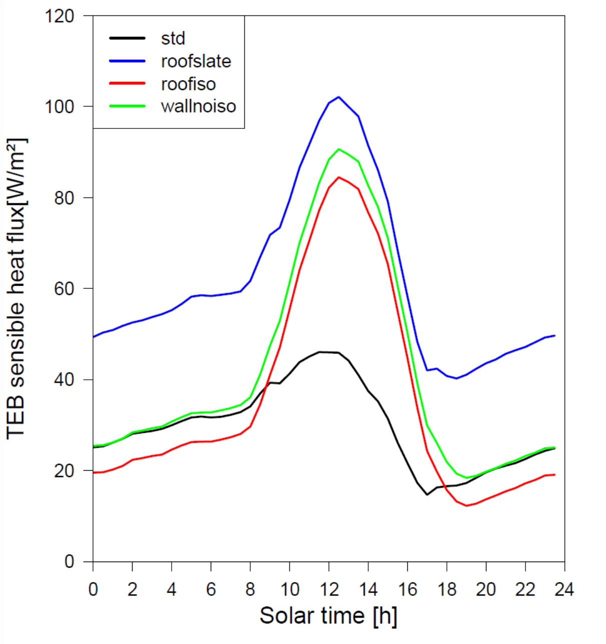
Better solution would be to introduce calculations for the deep soil below the buildings (e.g. 2 m)

What are the opinions of building simulation experts on how to treat the deep soil below the buildings?

Prepared experiments
- Impact of the roof and wall isolation

- **"roofslate"** (roof = 2 cm slate without isolation material)
- **"roofiso"** (roof = 2 cm slate + 8 cm isolation material)
- **"wallnoiso"** (walls are 25 cm pure brick)





Roof isolation very important
Wall isolation not so important
Might be artifact of one-node building model
Comments from experts?

Ideas for further sensitivity studies?

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