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A user-friendly multi-model platform to simulate urban evolution and urban climate in a context of adaptation to climate change

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In the recent years consulting services have seen a rapid increase of the number of requests related to urban climate. These requests generally concern the assessment of:

- urban areas vulnerability, particularly facing heat waves, in a context of climate change,
- urban planning policies, with their impact on microclimate and energy consumption,
- hydrological risks in urban areas.

The main challenges with such studies include:

1) the case-by-case treatment due to the heterogeneity in the requests (different cities, study area and scales, focus on different concerns, etc.),,
2) the gathering of homogeneous urban descriptive information,
3) the use of both urban and meteorological models and their coupling,
4) the transcription of urban development scenarios.

This paper aims at presenting the steps, methods, hypotheses and support which were implemented to overcome these barriers and to offer a user-friendly multi-model platform to simulate the evolution of the city and the urban climate over a century.

From a research approach ...

The National Center for Meteorological Research (CNRM - TURBAU) in partnership with Toulouse Urban Agency (AUAT), the European Center for Scientific Calculation Research and Training (CERFACS), the Environment and Development International Research Center (ENM-CIRED), the Environmental Geography Lab (GEODE), the Architecture Research Lab (LRA), Toulouse Mathematics Institut (IMT) and the French aeronautics, space and defense research lab (ONERA) led from 2009 to 2013 the ACCLIMAT Project (Adaptation au Changement CLIMatique de l'Agglomération Toulousaine) funded by RTRA-STAE. The objective of this project was to study the interactions between the processes of urban development, urban microclimate and climate change.

Meeting the climate challenge today requires states to reduce their greenhouse gases emissions, but also to take adaptation measures to mitigate the adverse effects of global warming on the population, economy and environment. The question arises particularly at the scale of the city, which is highly sensitive to climate change. Because of its high concentration of populations and activities in constant evolution and growth, the city is a complex system, in terms of number and diversity of actors (households, investors, policy makers), social and economic exchanges and heterogeneity of the urban fabric. In addition, urban form and materials create a specific micro-climate, characterized mainly by the urban heat island.

To address the issue of sustainability of the city, long term view is necessary, due to the time constant of both climate change and city evolution.

To have a chance to live in cities adapted to the climate by the end of the XXI century, it is essential to begin from now modifications in building design and technology, and evolution in urban planning strategies.

But so far there is no consensus or even clear idea of what needs to be done, much less how to do it: during the selection of urban development plans, it is relevant to get quantified and objective data, on cross-cutting issues, to assess - a priori - urban development scenarios, by taking into account climate change.

ACCLIMAT was conceived as a demonstrator for the Toulouse urban area, a numerical simulation tool for testing adaptation measures, identifying levers and estimating the efficiency of measures envisaged to adapt the city to the future climate. It aimed to give answers to practical issues:

- What socio-economic levers have an effect on urban expansion, over the century? What are then, for urban area of Toulouse, the various possible projections of expansion?

Which are the impacts - for various strategies of adaptation - of the interactions between climate change and urbanization on a city on the scale of century, in term of: urban climate, energy consumption, comfort of the inhabitants, economic and environmental costs? Scenarios of evolution were applied to the Toulouse metropolitan area and served to force urbanization models, as well as an urban-block model, and a climate model. Impacts were estimated through a set of indicators to assess and compare those different scenarios.

Prospective scenarios of evolution from 2010 to 2100 were built across the Toulouse area from analysis of major global trends (macro-economic, demographic, technology, etc.), then from local analyses by Toulouse Urban Agency, over three major periods (2010-2030, 2030-2070, 2070-2100) Demographics, local economy, new technologies, thermal regulation and urban planning are components of "integrated scenarios" representative of possible futures for Toulouse.

The relevant meteorological situations for the future climate in the region of Toulouse were extracted from climatic projections over Europe using a downscaling method.

Two urban models were coupled:

- the socio-economic model NEDUM (from CIRED), designed to reproduce the underlying mechanisms in the dynamics of an urban system (transport, housing, taxes);
- and the land use model SLEUTH*, adapted by GEODE from the model SLEUTH (Slope, Land Cover, Excluded, Urban, Transportation, Hillshade).

The resulting model, SLEDUM, allows to spatially simulate the possible evolution of urban sprawl, taking into account structural, socio-economic, geographical constraints and territorial planning decisions.

The GENIUS architecture model developed by the LRA/CNRM then simulates the evolution of districts and buildings. The multi-disciplinary modelling platform ensures the coupling of these different models and enables to simulate the evolution of the city on various scales till the end of the XXIth century for different scenarios,

Micro-climate over the urban area is modelled by a surface fluxes model (SURFEX, CNRM), including a town energy balance module (TEB, CNRM, Masson 2000) that computes energy fluxes within the buildings and artificial surfaces.

Atmospheric conditions (solar radiation, wind, precipitations) are prescribed to the SURFEX-TEB model either by using observations from a meteorological station (and then the Urban Heat Island is reconstructed following the Bueno et al 2013 method) or by coupling with a mesoscale atmospheric model (MESONH, LA/CNRM).

A perturbation due to climate change intensity can then been added to this meteorological data (Hidalgo et al 2014).
The micro-climate model enables to simulate the impacts of urbanism parameters (the shape of the city, the type of housing, the renovation rate, etc.) in different climate change contexts. Impacts are evaluated with respect to the energy consumption (both heating and cooling) and in term of thermal comfort.

The integration of scenarios and models on a single scalable platform was performed by the PALM coupler, developed by Cerfacs and ONERA and designed for the coupling of complex and/or heterogeneous codes, offering high performances facilities deployed through a user interface (task and code parallelism, numerical libraries, regridding toolbox, etc.). A configuration interface helped the user to select the appropriate scenario and a collection of indicators derived from model outputs facilitated the interpretation of the results.

The town characteristics are given through a Local Climate Zones (LCZ). Crossing information on the LCZ and on other indicators (such as the age of the buildings in the LCZ, or the use of them - residential, commercial, offices,...) allows to derive the physical properties of the buildings for TEB.

The main results of the ACCLIMAT project are that (Masson et al 2014) :

- The urbanized areas in 2100 strongly depend of the urban planning in the next 30 years.
- High-rise buildings influence negatively the Urban Heat Island (UHI). They induce warmer UHI in summer (due to lack of green areas) but reduce the UHI in winter compared to the historical dense city center (due to increased ventilation).
- The several possible future urbanization patterns that were simulated produce an increase of the UHI between 1°C and 3°C. In addition to the UHI, the climate warming signal range between +2°C and +6°C.
- A compact city increases the exposition of the population to heat in summer, especially because the population is more concentrated near the city center, where the UHI is the strongest. Furthermore, a green-belt strategy is efficient to produce a compact city in the next decades, but such a strategy must be re-evaluated in the far future (after 2050) if population continues to grow in the city : in that case, people may choose to cross the greenbelt and have a house on the other side. This would increase in the end the overall daily transport compared to a city that would have extended without the green-belt. This does not mean the green belt should be abandoned, but it should be replanned in the future.
- The main levers are : urban model (compact, spread-out, …), vegetation and behaviours of the inhabitants. Indeed, the choice of target temperature for heating or air conditioning, or the use of shelters in summer can have more impact than technical aspects, such as the renovation of the buildings. This means that actions to both people and architects are necessary to improve building scale energy efficiency.

.... to an application for consulting services

The ACCLIMAT project demonstrated the scientific and technical feasibility of a multi-disciplinary study of a large town evolution, over a century and for various scenarios, and the associated climatic trends, using 5 numerical models coupled within a single integrated system.

Then, the main goals of the technology transfer are :

- to extend the current capabilities of the prototype, in order to (i) perform simulations on any large town, including coastal and border sites, (ii) change the resolution towards lower (for cost reduction) or higher (e.g. for impact studies over a district) resolutions, (iii) use more recent climate runs as atmospheric forcing and (iv) allow simpler studies (urban evolution only or stable town characteristics);
- to simplify and extend its use, e.g. adding multi-users management and remote access, designing a user-friendly interface, together with a drastic reduction of the required input data and pre-processing steps;

A gain in efficiency by around 40% is expected by using the new platform instead of the previous research tools, when available.

The transfer is achieved through a close cooperation between research and consulting services.

Simplicity and efficiency

The quest for simplification while maintaining the relevance of the platform for the targeted studies took place at four levels:

- conduct an analysis of models to keep,
- limit dramatically the number of input data,
- restrict or simplify pre-processing and post-processing steps,
- provide support to prepare, launch and analyze experiments.

Changes in urban models

The model used in the ACCLIMAT research platform to simulate the socio-economical scenarios is the model from the CIRED (NEDUM). The coding, preparation of input data, calibration of this model require strong expertise from CIRED economists. As a consequence it was decided to replace it by a simpler model, PrepVille, developed specifically for the new platform and exchanging data with GENIUS and SLEUTH* as NEDUM did.

An economic scenario (growth or decay of the town and its suburb) is now prescribed via an increment every 10 years of the global urbanized surface and the demography change. Among the income of new inhabitants, the proportion of those choosing to live in new districts is also specified.

These are spread over the domain according to simple rules, such as:

- no building along motorways, close to the edges of the domain, in isolated areas;
- no new inhabitants in non residential areas;

- new floor surface proportional to population increase, if any, with fixed ratios depending on block types.

Another major change is the introduction of a new module, ConfigVille, which allows:

- to specify the domain, extension and horizontal resolution, at a single level; the mesh size is now the same for all urban models. Previously SLEUTH* was working on a finer grid and NEDUM on a coarser one;
- to reduce the number of mandatory input maps to one; a first guess for the urban maps required as input for SLEUTH* is derived from the input map of GENIUS. Providing finely tuned data is still allowed.

This and further changes, e.g. to allow coastal or border towns, should allow to run the platform for any city in France. Some steps are still missing for overseas domains.

A simplified town description as single input map

GENIUS relies on a description of urban areas and surroundings by blocks, mapped on the regular grid now common to all urban models, and distributed within 9 predefined types, according to building height, density or use. The specification of block types and their main characteristics, hereafter called "block map", is now the key pre-processing step.

For ACCLIMAT, the initial block map was derived from a detailed statistical analysis based on IGN, the National Geographic Institute, (for land use and building description) and INSEE, the National Institute of Statistics and Economic Studies (for socio-economical features) databases. At least thirty parameters are used to describe blocks: position, topographic data (sea, rivers, vegetation coverage, height, slope,...) and use and type of building, roads, population... at a scale of 100 to 500 m. To simplify the construction of such maps, a set of tools relying on the use of a Geographic Information System and R scripts has been coded. The main input is the IGN "BD TOPO" database (a 3D metric resolution database that describes topography and buildings over France). Whenever possible, topographic and urban parameters are described "exactly" for each mesh. Assumptions are required however to derive some fields, such as block type, spreading of inhabitants, building orientation and use, ...

Further adjustments can be performed to refine the description or simulate changes. In the long term, using maps from the MApUCE ("applied Modeling and urbAn Planning laws; Urban Climate and Energy") project will be considered.

Preparation of the large-scale forcings now integrated into the platform

A database of meteorological situations of interest for impact studies in urban climate has been installed on the platform.

Two modules (PrepMNH and PrepSURFEX) were added to the platform, and generate from this database the initial and lateral boundary conditions for the atmospheric 3D model MesoNH or directly the atmospheric forcing for the surface model SURFEX.

A work on the automatic management of MesoNH and SURFEX grids and integration in the MesoNH surface fields of the city changes were associated with these components.

Human-Machine Interface (HMI)

To help engineers to launch and manage their experiments, a web interface has been developed, and covers the following main features:

- Remote access,
- Able to operate and support the workflow in multi-users / multi-projects / multi-experiments configurations,
- Versioning (by default, set to the latest version),
- Preparation and run of the simulations,
- Visualization of some simulated output parameters (to control the simulation),
- Technical Assistance.

This web interface automates as much as possible what can be. It offers user the opportunity to change the default settings.

It is a component of a classic 3-tier web architecture.

A set of chronological tabs helps the engineer in the various stages of the preparation:

- selection of the city,
- association to a project,

- choice / construction the town evolution scenarios,
- choice of the modelling platform parameters (models turned on/off),
- climatic and urban cycles definition,
- choice of the weather pattern (among a set of pre-identified and available typical weather conditions).

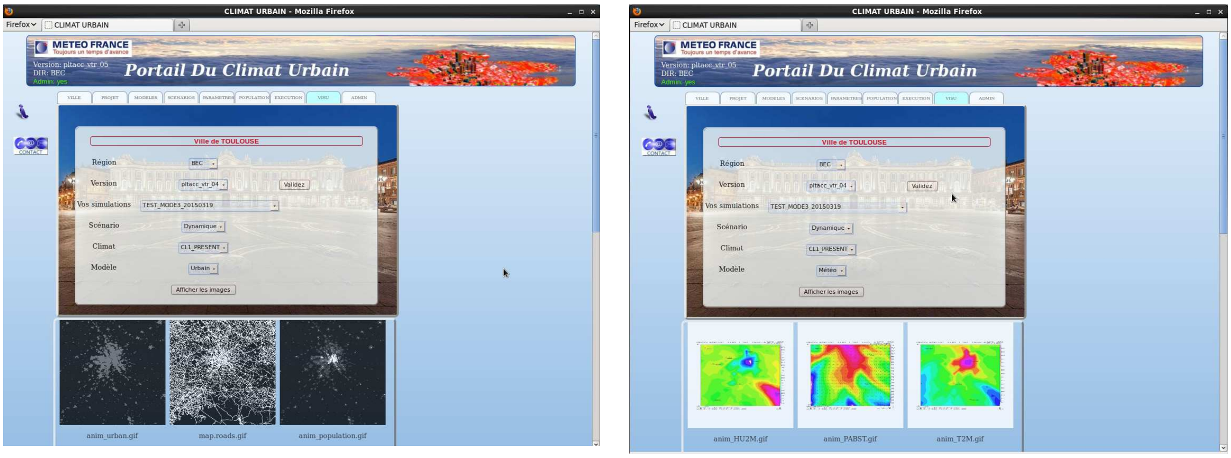

Figure 1 : Example of the HMI basic viewer (mock-up view) for urban models outputs (left panel)and weather models outputs (right panel)

Post-processing

The ACCLIMAT set of available output fields, describing either climate or town, has been updated, taking into account the suppression of NEDUM model and adding new meteorological patterns. It may be refined for each experiment.

R scripts will be available to derive "on demand" composite diagnostics from these fields, e.g. mean values of meteorological fields over a season for present and future climates. Most of these indicators were defined during previous projects (ACCLIMAT, MUSCADE and EPICEA). The choice of a widely used coding language and the modularity of the basic set of scripts should facilitate the development of new diagnoses according to new studies emerging needs.

The overall set of output fields cover the following fields of interest :

- meteorology / climate (wind, temperature, humidity) : to document town-land, indoor-outdoor, day-night contrasts for instance;
- population : growth, distribution between districts, comfort (regarding climate, air-cooling or heating, size of flats, ….);
- urban planning policies: as the renewal rate of urban park, greening index of the town, surface consumed by the arrival of new residents ...
- energy and environment: electric power demand, vegetables roofs, surface of public greenspace by inhabitant …

Further tests and perspectives

The simplifications brought to the prototype will be tested on Toulouse city and will be assessed on some key indicators and systemic scenarios inherited from ACCLIMAT.

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