Adapting cities to climate change: A systemic modelling approach

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A R T I C L E   I N F O

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A B S T R A C T

Societies have to both reduce their greenhouse gas emissions and undertake adaptation measures to limit the negative impacts of global warming on the population, the economy and the environment. Examining how best to adapt cities is especially challenging as urban areas will evolve as the climate changes. Thus, examining adaptation strategies for cities requires a strong interdisciplinary approach involving urban planners, architects, meteorologists, building engineers, economists, and social scientists. Here we introduce a systemic modelling approach to the problem.

Our four-step methodology consists of: first, defining interdisciplinary scenarios; second, simulating the long-term evolution of

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[1] The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors. They do not necessarily represent the views of the International Bank for reconstruction and Development/World Bank and its affiliated organizations, or those of the Executive Directors of the World Bank or the governments they represent.

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cities on the basis of socio-economic and land-use models; third, calculating impacts with physical models (such as TEB), and; finally, calculating the indicators that quantify the effect of different adaptation policies. In the examples presented here, urban planning strategies are shown to have unexpected influence on city expansion in the long term. Moreover, the Urban Heat Island should be taken into account in operational estimations of building energy demands. Citizens' practices seem to be an efficient lever for reducing energy consumption in buildings.

Interdisciplinary systemic modelling appears well suited to the evaluation of several adaptation strategies for a very broad range of topics.

1. Introduction

Climate projections have foreseen both global warming, sea level rise and an increase in the frequency and intensity of extreme events (IPCC, 2013; Solomon et al., 2007), such as heavy rain and storm events (hurricanes, monsoons, and floods), heat waves, desertification, and giant forest fires. The IPCC assessment reports (IPCC, 2013, 2007b) confirm that greenhouse gas emissions have to be drastically reduced to limit on-going global warming and the pace of the resulting climate change. These reports also acknowledge that adaptation of societies to a new climate context is of prime importance.

These issues have particular relevance to urban areas where valuable assets are concentrated and more than half the world's population resides. Moreover, in some instances the projected global-scale changes can be exacerbated by city-scale phenomena, such as the formation of heat islands (UHI), which during heat wave events, may result in many deaths (Gabriel and Endlicher, 2011; Johnson and Wilson, 2009).

Each of these project climate changes will have an impact on cities that will probably necessitate different adaptation strategies, depending on their specific features (and the interactions between them), the city characteristics and location, the local governance and the level of social and economic development.

At the international scale, the assessment of urban vulnerability to an altered climate is an emerging research topic as shown by projects such as *Engineering Cities: how can cities grow while reducing vulnerability and emissions*?[2] (Tyndal Centre, UK), *Urban lifestyles, sustainability and integrated environmental assessment*"[3] (Postdam Institute for Climate, Germany) and the *New-York Climate and Health Project*.[4]

These works tackle different aspects of environmental risk in cities: flood risks (De Roo et al., 2007) and water system management (Rosenzweig et al., 2007); epidemiological impact of ozone and fine particle pollution (Bell et al., 2007); and heat-related mortality (Dessai, 2003; Knowlton et al., 2007) or discomfort (Kusaka et al., 2012). Environmental risks and vulnerability are often quantified using empirical and statistical approaches (Bell et al., 2007; Dessai, 2003; Knowlton et al., 2007) instead of physically-based models (Kusaka et al., 2012; Masson et al., 2013). Most of them, however, are not based on a interdisciplinary (systemic) approach that accounts for the social, economic and physical processes that interact together at the city-scale; instead they are often limited to one or a few closely related scientific fields.

[2] See: http://www.tyndall.ac.uk/publications/other-tyndall-publications/engineering-cities

[3] See: http://www.pik-potsdam.de/research/past/1994-2000/europa/euro9.html.

[4] See: http://www.mailman.columbia.edu/academic-departments/environmental-health/climate-health-program/new-york-climate-and-health-project.

In the field of atmospheric sciences, the BRIDGE project (Chrysoulakis et al., 2013) proposes a multi-model approach to simulate the impact of (specified) urban scenarios on the local atmosphere in terms of air pollution, CO_2 emission and the UHI. However, the city itself is not modelled either in terms of its metabolism or evolution over time. Kusaka et al. (2012) have studied the interaction between climate change scenarios and the UHI for three cities in Japan. They show that the main increase in temperature is governed by the global climate change signal and that the UHI does not change based on scenarios that do not permit the cities under study to evolve over the time span of the study. However Aguejdad et al. (2012) show that changes of urban patterns under the assumption of an unchanged climate influences the extent and magnitude of the UHI. Moreover, using a high-resolution atmospheric model, both De Munck et al. (2013) and Tremeac et al. (2012) show that, even if the structure of a city does not change, an increase in air conditioning use can lead to an increase in the UHI by 2 °C in the centre of Paris. Masson et al. (2013) show that such an increase of the UHI can be reduced by changes in the strategy for sub-urban and rural crops and increases in the forested areas in the region of Paris. These few examples already show the variety of processes that can interact within the frame of urban meteorology alone when we consider the adaptation of cities to climate change. The results of the EPICEA project[5] highlight the potential effect of adaptation measures aiming to limit the intensity of the UHI over a big city (Lemonsu et al., 2013) by modifying the surface energy balance. These techniques are widely known (e.g. surfaces that reflect high proportions of solar radiation, high infrared albedo of roofs and wall surfaces, greening and watering of urban surfaces) but a detailed simulation of heat and mass transfers between the built area and the atmosphere is needed to assess their effect. An average reduction of 1 K over space and time may appear to be a modest result but such an effect could greatly influence the recorded mortality. The temperature decrease may be locally and temporarily higher depending on the many factors that drive the energy balance. This project also addresses some side effects of implementing adaptation measures (feasibility, cost, maintenance, and acceptability).

However, the main point is that none of these studies who have considered climate change and cities have allowed the city to change (either in form or function). Furthermore, the adaptation strategies that are proposed are mainly based on environmental benefits (Rosenzweig et al., 2007) but hardly investigate their cost and socio-economic consequences, which can sometimes be negative (Rosenzweig et al., 2011).

This paper presents a systemic (or interdisciplinary) modelling methodology to provide some initial insight into the interactions between climate change, city structures and urban economies.

This work was carried out within the framework of three coordinated projects[6] (VURCA, MUSCADE and ACCLIMAT), each of which use this systemic methodology to examine cities can adapt and mitigate to aspects of climate change. These aspects include

- Adaptation to one type of extreme event, that of heat wave intensification;
- Mitigation of climate change by reducing energy consumption and;
- The impact adaptation scenarios on several human comfort and climatic indicators for urban areas.

The scientific challenges to developing a systemic modelling approach are discussed in Section 2. This approach requires that models designed for different purposes are coupled; the coupling strategy is presented in Section 3 and the main characteristics of the individual models are presented in Section 4. A validation on the cities of Paris and Toulouse follows in Section 5. The interdisciplinary indicators that result from this approach are shown in Section 6 and illustrative results on projections for the future of Toulouse in 2100 are given in Section 7.

[5] See: http://www.cnrm-game.fr/projet/epicea.

[6] See: http://www.cnrm.meteo.fr/ville.climat. The VURCA and MUSCADE projects focused on the Paris urban area, while the ACCLIMAT project studied Toulouse city area (in south-west France).

2. Scientific challenges

2.1. The city: a complex system

Each city is concentration of population and capital stocks (housing, production, water delivery, transportation and infrastructures) that comprises a complex system with social, economic and environmental aspects. Each of these aspects has its own rules of behaviour and evolution but each is closely linked with the others. For example, people will choose their housing according their preferences, the local amenities, distance to their workplace, and their budget (Hamilton et al., 2010; Brasingtona and Hite, 2005; Bjerke et al., 2006). The need to feed the population shapes the agricultural land around the city and beyond (even on other continents) and impacts the city environment, while interacting with the evolution of people's eating habits and transportation networks in the long run (Billen et al., 2012).

Such complex interactions lead to several scientific challenges:

(1) First, studying even a part of these interacting processes requires a strong interdisciplinary approach. In this work, studying urban climate evolution and building adaptation strategies of cities involved urban planners, architects, meteorologists, building engineers, social scientists, geographers and economists.
(2) Second, numerical modelling is an essential tool for the global comprehension of the city system and the underlying processes, which operate at different spatial and temporal scales. The interactions among the system components cannot be apprehended by human expertise only.
(3) The systemic modelling approach, which is interdisciplinary by nature, must link models designed for different purposes (e.g. planning and urban climate models). This requires a broad comprehension of the information exchanged between the models themselves and of the links between scenarios and models (each scenario driving all models in a coherent manner).

The problem of the adaptation of cities to climate change induces an additional scientific challenge, that of the time horizon.

2.2. A 2100 time horizon

Addressing climate change and cities entails the examination of both the changing climate and city system. Resolving this problem means that several processes need to be considered, each of which has a typical duration:

(1) Projections of climate change have a horizon of a century; for example, depending on the GES emission scenario, global warming will cause a temperature rise of several °C by in 2100 and more beyond (IPCC, 2013).
(2) Structural modifications in cities occur slowly (Grazi et al., 2008a). For example, in most parts of Europe, city structures have grown up over centuries (Grazi et al., 2008b) and an urban building has a lifetime of 50 to more than 100 years (Balaras et al., 2007; Gusdorf et al., 2008).
(3) Lifestyles also evolve over lengthy timescales depending on the influence of available technologies, social history, etc. Education plays a relatively strong role in such evolution, meaning that the time-scale can extend over one or two generations.

In other words, if cities are to be adapted to the projected future climate, it is necessary to start adaptation now by modifying city structure, building design, urban planning habits, etc. Dealing with this timescale raises some scientific challenges for the systemic approach: the scenarios employed to the year 2100 must be constructed coherently for the different disciplines (climate, economy, technology, urban planning, etc.) included and the models adopted must be pertinent for such a time-scale (and validated on a similar period of the past). Moreover, the uncertainties associated with the results must be quantified (as has already been done for climate projections in IPCC reports).

3. The systemic modelling approach

3.1. Impact modelling versus systemic modelling

Usually, in disciplinary studies on climate change, some urban impacts are quantified using a number of models. The description of the city for which they are calculated is provided through scenarios (see Fig. 1a), which are constructed from the expert knowledge of urban planners and scientists (who can include some modelling results within their design) and/or from people who have influence or interests in the local area. This approach requires significant resources and human expertise, so it is likely to provide a limited number of scenarios, focussing on a limited area over a limited time horizon. The vision of urban planners is linked to urban regulations and operations, which typically make provisions for up to 20 years ahead.

The BRIDGE project (Chrysoulakis et al., 2013) comes into this category, as the energy atmospheric models were fed by alternative scenarios of localized urban planning interventions on the five European cities tested.

In some other works, the scenarios of the cities are even simpler in that their description is constant in time. This can be because the authors wish to evaluate the impact of climate change or a few parameters alone. However, this strongly limits the range of urban adaptation strategies that can be tested; for example, Krayenhoff and Voogt (2010) present a review of the modelling of the impact of white roofs on air temperature. Alternatively, the researchers do not expect that the cities under study will grow, even by the end of the century. Kusaka et al. (2012) explain that Japanese cities are not likely to grow any further because they are already very large and the population of Japan is decreasing. As a consequence, the descriptions of the three cities examined were kept constant for the period studied (2010–2070).

To deal more accurately with the question of adaptation of cities to climate change, it is necessary to consider a time-scale of a century or more, as well as a much broader range of disciplines.

The systemic modelling strategy used here is therefore much more ambitious than classical impact modelling in terms of the processes simulated and the perspectives employed to quantify different strategies for adapting cities to climate change. To implement this approach a strong, broad interdisciplinary panel of researchers is needed. However, the crucial difference between the impact and systemic modelling approaches is that the latter allows the city to evolve using simulations that consider long-term trends, which affects its development, rather than using prescribed scenarios.

Systemic modelling offers several advantages over the alternative. Firstly, it ensures that processes driving the evolution of a city are consistent from an interdisciplinary perspective. Secondly, it permits many more projections of the city to be simulated (allowing sensitivity to be analysed and uncertainties to be quantified), some of which may not have been considered at the outset. For example, a large peak in oil prices will lead to a strong increase in energy costs in the short term (2030–2040), but may not have so much impact in the long term (2100) because economic pressure induces the development of alternative technologies (Viguié et al., 2014). In this case, city expansion in the future may

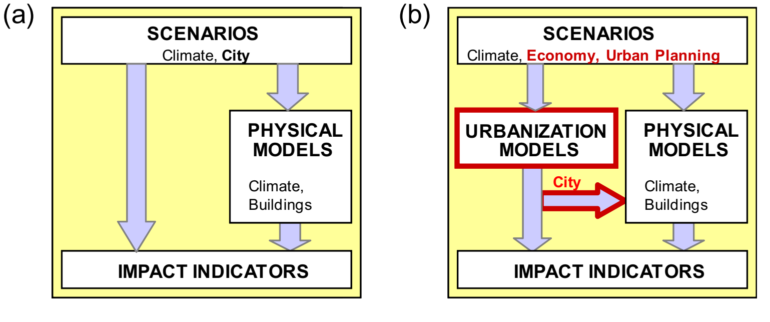


Fig. 1. Approach for (a) impact modeling; (b) systemic modeling.

be much less constrained by oil prices than is usually believed. The systemic modelling of the city simulates an outcome that is internally consistent with both the scenarios developed and the processes embodied by the equations in the linked models.

3.2. Overview

The systemic modelling approach combines prospective scenarios (Godet, 1986) and spatially-explicit models (Houet et al., 2010). It can be summarized as follows (Fig. 1b):

First, interdisciplinary scenarios are defined. Marchadier et al., 2012, considered scenarios based on the IPCC projections, global economy developments including energy costs and per capita income (see Viguié et al., 2014 for details), changes to the local economy (for example, is the city in crisis or not compared to the rest of the country?), technological innovations (in buildings or transport), lifestyle changes (e.g. use of air conditioning), and urban planning initiatives (green city, dense city, etc.). These scenarios do not claim to guess what the city will be like but they do allow us to explore possible city evolutions. Moreover, they can be used in two distinct ways: to forecast based on the existing urban character and; to backcast by illustrating what we would (not) like the city to be. Depending on the other factors (mainly previous history of the city, demography and economy), these urban planning options will have more or less effect on the final shape of the city.

Second, city models are used to simulate long-term urban expansion. The broad shape of the city expansion can be simulated by a socio-economic model (NEDUM is used here), which is driven by general and robust economic laws. This model can be coupled with a geographical model (SLEUTH is used here; see Clarke et al., 1997; Clarke and Gaydos, 1998; Clarke, 2008) to provide greater spatial detail and incorporate urban planning decisions more explicitly. Similarly, this geographical model can be coupled to an architectural model that describes outcomes at a fine resolution. Here, we employ an Urban Climate Zone classification to describe how the urban form of each city block will evolve in response.

Third, the impacts (meteorological and others) are simulated by physical models. A building energy model is included in an urban canopy scheme that is coupled to the conceptual or full atmospheric models to take both climate forcing and UHI reciprocal action on the city (energy consumption, comfort, etc.) into account.

Finally, indicators quantifying the adaptation strategy (for each scenario) are calculated and compared.

4. Brief presentation of the models

4.1. The urban expansion models

The main criterion for the choice of the urban expansion model is to have a model that can produce projections of the city structure over the very long term for varying scenarios that may include a significant change in the environmental context, such as an oil crisis. The urban models used by urban planning agencies (such as TRANUS, Barra, 2005) often use rules based on the extrapolation of past trends, which may be valid for a short period into the future (20–30 years). Here, we have selected the Non-Equilibrium-Dynamical Urban Model (NEDUM) to simulate the expansion of the city over long periods; it is driven by economic considerations and general laws that make the model robust and suitable for long-term simulations. However, the model will lack some small-scale details (e.g. urban concentration due to local amenities). In order to be confident in its pertinence for the century to come, NEDUM has been validated on the past 100 years (Viguié et al., 2014).

The model is based on three key mechanisms:

(1) Households choose their accommodation location and size by making a trade-off between transport time to work and the price of real estate.
(2) Real estate developers optimize profit by constructing tall buildings where land is expensive and houses further from the city centre.

(3) Variable time scales for different processes, for example rents adjust quickly but building construction is slower to external forces.

Numerous databases that describe the actual city are needed for the simulation including the transport network and some economic data (e.g. per capita income). Other important data required by the NEDUM model are the areas where building is not permitted (e.g. rivers, parks, protected zones). The simulation results generate a great deal of economic data but the crucial data that are used further in our modelling chain are:

- A map of the quantity of floor area built for residential housing,
- A price map for rentals and,
- The total newly urbanized surface area (including roads, gardens, car parks, etc.).

These data are generated at 10-year intervals.

In order to refine the spatial allocation of the urbanized areas at small scale, a geographic cellular automata urban growth model was modified (called hereafter SLEUTH* – Doukari et al., 2013) so that it could be coupled to NEDUM (Fig. 2) and simulate the scenarios for 2100. Instead of estimating the urbanization growth rate from previous urban maps (hence extrapolating past tendencies), SLEUTH* becomes a scenario-dependent model, i.e. it does not require any calibration steps but depends strongly on user (urban planning preferences) defined parameters. It now takes a given amount of urbanization (that is provided by NEDUM every 10 years) into account and relocates it by considering geographical amenities (slopes) and urban planning preferences. The latter includes whether construction is to occur near already built-up areas and roads or disseminated in the countryside or what parts of the landscape are to be protected from urban development. The allocation of new urban areas

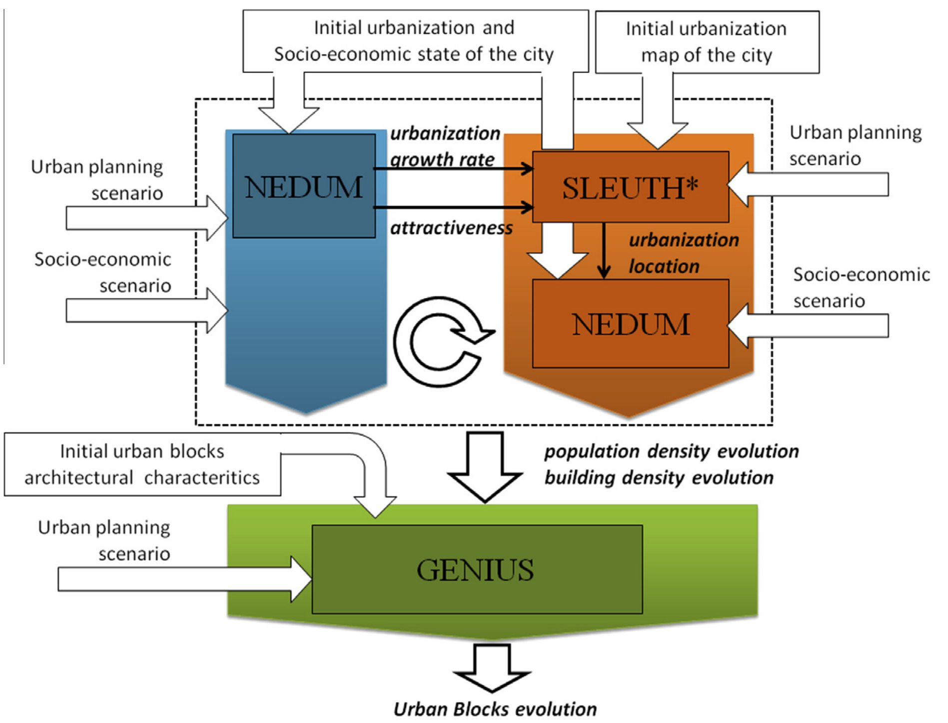
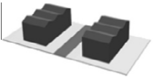
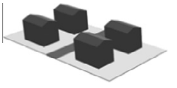
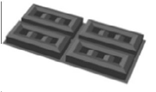
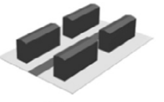
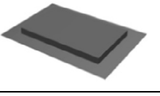


Fig. 2. Strategy for coupling economic expansion model (NEDUM), geographical model (SLEUTH modified) and architectural model (GENIUS). Models are integrated and coupled together every 10 years with the Open-PALM coupler.

Table 1
The seven typical blocks.

Selected LCZ		Correspondence with Steward and Oke LCZ
Continuous pavilion		(3) 'Compact low rise'
Discontinuous pavilion		(6) 'Open low rise' and (9) 'Sparsely built'
Continuous block		(1) 'Compact high rise'
Discontinuous block		(5) 'Open mid rise'
High-rise tower		(4) 'Open high rise'
Ancient center		(2) 'Compact mid rise'
Industrial building		(8) 'Large low-rise' and (10) 'Heavy industry'

is also influenced by integrating a map generated by NEDUM that describes the attractiveness of the area under study based on the cost of transport and the price of land.

NEDUM and SLEUTH* were coupled using PALM software[7] and applied to the city of Toulouse. Independently, these two models have limitations for simulating urban development (Aguejdad et al., 2012) but together they complement each other and the coupling offers mutual benefits.

4.2. The architectural model

Once the location of the new urban areas and the quantity of building to take place there is simulated, we still need to know what type of construction is likely to take place. Even in older urbanized areas, population increases can induce a densification of the urban fabric and a destruction/reconstruction process. In order to reproduce these effects, a new architectural program, GENIUS (the GENerator of Interactive Urban blockS) has been specifically developed in the framework of our projects.

The strategy underlying to the development of GENIUS is based on identifying the main characteristics of urban morphology at the block scale (typically 250 m by 250 m), which allow typical urban forms to be identified. This urban block method can be compared to the Local Climate Zones (LCZ) (Stewart and Oke, 2012; Oke, 2008) approach used in urban climatology (Table 1). In GENIUS, we have adopted the LCZ descriptors most relevant for European cities (according to the nomenclature and numbering of Stewart and Oke, 2012) and applied them to the urban block scale. For our purposes, an additional LCZ class (monuments), is added to allow a better architectural description and other LCZ classes are merged.

Each block then is categorised into an LCZ and is characterised by about 60 indicators. These variables describe urban form (fraction of vegetation, of buildings, height of buildings, etc.), architectural

7 http://www.cerfacs.fr/globc/PALM_WEB/.

features (e.g. the date of construction of the buildings, majority type of heating equipment, etc.) and social characteristics (for example, residential, offices, commercial, industrial or agricultural use). All these indicators are crucial in our modelling suite, as they make the link between the urbanization and the characteristics of the buildings for the building energy model.

To derive these data, an analysis of the existing 3D building databases was made in order to express the real city in the form of a map of block-scale LCZs (cf Fig. 3). The evolution of these LCZs in the future is driven by the flux of construction of floor area (m2) in each block at ten year intervals. The way the indicators vary as a function of the others is shown in Fig. 4. Note that some information on urban planning scenarios can also influence the future urban forms in the city so that, for a given built floor density, one type of building or another that typify an LCZ type may be favoured.

4.3. The urban climate and energy consumption model

The final step is to simulate energy consumption that accounts for the UHI and all other driving factors (such as climate change or city evolution). However, while detailed building models (such as Energy +) represent the details of the buildings very well (in terms of both interior and envelope architecture), they do not consider the impact of buildings on the outside weather, so the effect of the UHI is neglected. Typically, the meteorological conditions that represent ambient conditions for these models come from an airport meteorological station outside the city.

Taking the urban and global climate changes into account presents two challenges: (1) how to account for urban scale effects like the UHI and (2) how to include climate change scenarios from a climate model to the city scale.

The first issue is solved here by introducing a building energy model (BEM) (Bueno et al., 2012a, 2012b; Pigeon et al., 2014) into the Town Energy Balance (TEB) model (Masson 2000). This BEM works within the relatively simplified urban geometry of TEB but all the important processes are taken into account: internal mass, internal energy balance, windows and solar radiation, shading devices, internal gains, heating/cooling devices (including waste release to the atmosphere) and infiltration/ventilation, and some uses are simulated (shading device use, natural ventilation strategy). In addition, in

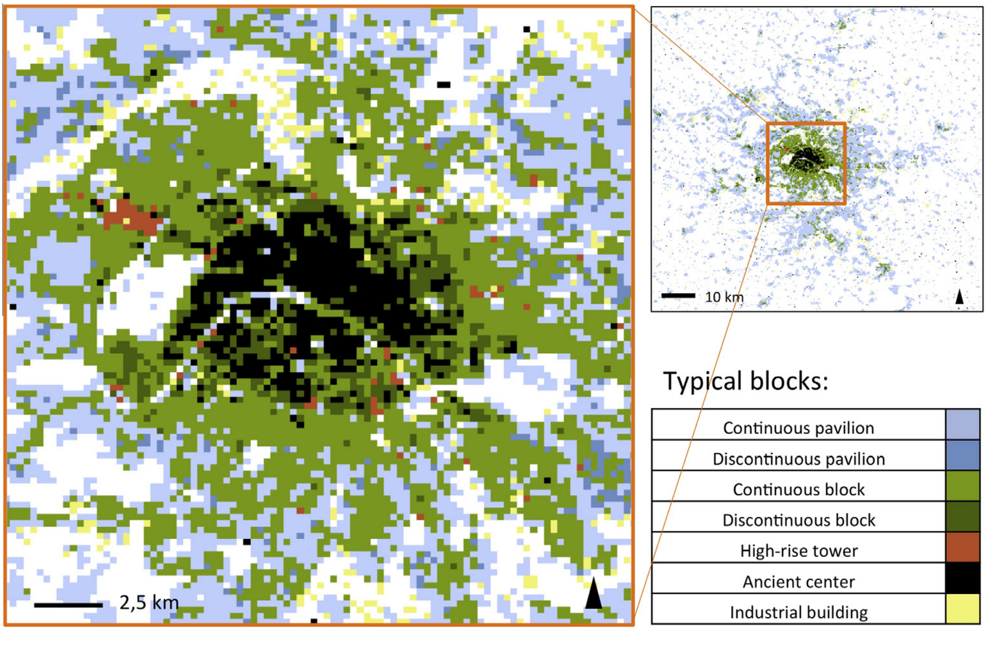


Fig. 3 . Description of Paris (year 2008) in terms of Local Climate Zones. Grid mesh is 250 m.

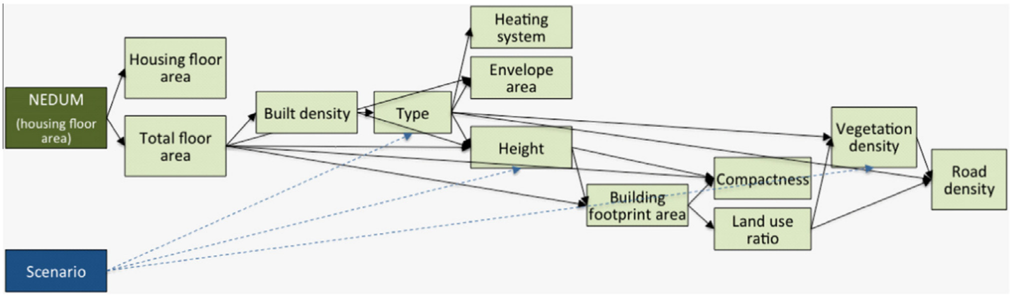


Fig. 4. Causal relations for evolution of indicators in GENIUS architectural model.

order to be able to assess some adaptation strategies based on urban vegetation and fine urban structure, gardens are now represented (with the Interface-Soil-Biosphere–Atmosphere ISBA scheme, Noilhan and Planton, 1989) within the canyons themselves, canyons that can now have a specific orientation in TEB (Lemonsu et al., 2012), and a greenroof module (also based on ISBA) is implemented (DeMunck et al., 2013).

The second issue is more difficult to address. How can we best represent the impact of cities (typically the UHI) in the context of long-term climate studies? Current global climate models lack two key elements to be able to simulate the UHI. First they do not have the physics dedicated to urban surfaces (such as TEB). Second, their resolution is of several tens of kilometres at best, even for regional climate models. So cities and their climate effects cannot be represented explicitly. Very recently, studies have been made of climate change over several decades at a regional scale (3-km resolution) using climate models (such as the COSMO model with TEB in Berlin Trusilova et al., 2013) but such models cannot be used to create long-term scenarios yet. This is an acknowledged problem with existing climate change scenarios; see for example the UK Met Office (UKCP09 web portal[8]) or Météo-France (Drias web portal[9]). The former states that 'UKCP09 does not include the process by which urban areas store and generate heat, creating a local climate which has significant implications under climate change'. As a result, down-scaling of the simulations from climate models to urban scale is necessary.

Here, two down-scaling approaches were considered. The first is to couple the surface with a full atmospheric model. Kusaka et al. (2012) simulate the UHI of Tokyo, Osaka and Nagoya at 3-km resolution for the month of August in 2070. Similarly, Masson et al. (2013) and De Munck et al. (2013) simulate heat-wave days over Paris at 500 m and 250 m of resolution. However, such simulations are extremely expensive in CPU time, especially if a detailed description of the city is included. One means of overcoming this issue is to coupling the surface and the atmosphere at different resolutions (typically 250 m for the city and 1–2 km for the atmosphere). This allows a better physical representation of the atmosphere than in the first approach, but still at a cost of more simulation time. The second approach, which is faster and provides longer simulations, is to couple TEB (and ISBA for urban vegetation and in the countryside) within a simplified model of the atmospheric boundary layer (typically 1 km high by day and 200 m by night) that is driven by the surface-atmosphere energy fluxes (Bueno et al., 2013). Then, the simulation is driven on the countryside either by observations (for present climate) or climate scenarios (climate models represent the countryside as only water and vegetated surfaces, not cities). This is done following the methodology described in Hidalgo and Masson (2013). This is the approach taken in this paper.

Now that our atmospheric models have the adequate physics, the final task is to link these to the city characteristics (as described by the block-scale LCZs), which are generated by the urban development models. This is mainly done through the GENIUS architectural model that links the LCZ parameters to the TEB model. Some of the important data (such as geometry and land cover) are directly

[8] http://www.metoffice.gov.uk/services/climate-services/uk/ukcp.
[9] http://www.drias-climat.fr.

associated with each grid cell and its LCZ characteristics. Other data is acquired from architectural expertise that connects built parameters to LCZ class based on current building type, date of construction and likely renovation and future building norms. For example, zinc roofs are associated with old buildings (construction date before 1900) in Paris and non-industrial brick walls are associated with old buildings in Toulouse. Some experimental measurements have documented the radiative properties of these surfaces (Seow et al., 2012), which can have a significant impact on energy consumption.

5. Validation of the models in the past

Before using the coupled models to quantify the benefits/limits of different adaptation strategies, two validation procedures were implemented in the aim of determining whether the model was able to simulate expected changes (scenarios). The first consisted of sensitivity tests to check that each function performed correctly and the second assessed how well the model simulated changes in the past and up to the present. This was done in several steps, first with each model alone and then with several models coupled.

The economic model NEDUM has been validated by comparison with the observed expansion of the Paris (Viguié et al., 2013) and Toulouse urban areas for the past century. The validation on Paris started from 1900 (with all the difficulties this supposes in gathering the necessary data for such a long time ago). The model was able to reproduce the expansion of the city (size and also pattern) at several stages in the 20th century, and also its socio-economic characteristics (rents, population density, housing density, dwelling size, etc.).

The geographical model SLEUTH* was tested through a set of sensitivity tests and on Toulouse metropolitan area over a period of 16 years (1990 – 2006) (Doukari et al., 2013). This time span is pertinent because the model is not designed to reproduce the long term evolution itself (this is the role of NEDUM) but to refine the allocation of a known amount of urbanization. Note that, for SLEUTH*, a calibration is performed on the past of the parameters of the model in order to accurately simulate several spatial indicators of the urban extension of the city and also to derive suitable values for a future 'business as usual' scenario. Other scenarios are then defined as variations from this one. The model assessment proved the ability of SLEUTH* to handle the simulation of several urban structures that reflect urban planning strategies. The model could then be used for forecasting.

NEDUM and SLEUTH coupled together were intensively tested on the city of Toulouse. Sensitivity tests assessed the capacity of each of the models to integrate the temporary data produced by the other at an annual time step. Fig. 5 and Table 2 show an example of coupled NEDUM–SLEUTH model performance in simulating a plausible urban pattern compared to 2006.

Verifying the ability of the architectural model GENIUS to reproduce the evolution of urban forms at block scale was more difficult because of the lack of building data over a lengthy period (50 years or longer). However, as buildings have a long lifetime in European cities, we could use information on existing buildings (for which date of construction was known) to check if GENIUS was able to simulate their construction. The evolution of the density of construction, in terms of floor area, was not available but that of the population was well known (with good spatial resolution) and was used as a proxy. The GENIUS model was able to reproduce the construction of 91% of the LCZ types adequately; the construction date of these LCZ was acceptable, with 66% of buildings built at the right time, i.e. correctly within the ranges 1962–1974, 1975–1989 or 1990 onwards. Given that there are uncertainties on the construction dates from the census data itself, we consider this a good result.

The simplified urban boundary layer model following Bueno et al., 2013 was improved to work in 2D instead of only in 1D. The rural conditions needed to force this simplified model came from Toussus airport, located 20 km from Paris but nevertheless in a non-urbanized area. We carried out the validation on Paris against both observation data and a high-resolution atmospheric model. The validation against the observations ran from 1998 to 2011, for minimum and maximum temperatures. There are 5 observation stations in the historical centre of Paris and its dense suburbs (by far the largest number of routine meteorological observations in a French city). We also extended the validation by comparing the simple weather generator to a complete high resolution atmospheric simulation (MesoNH model) performed over the Paris region at 2-km resolution during 2011 (Lac et al., 2013).

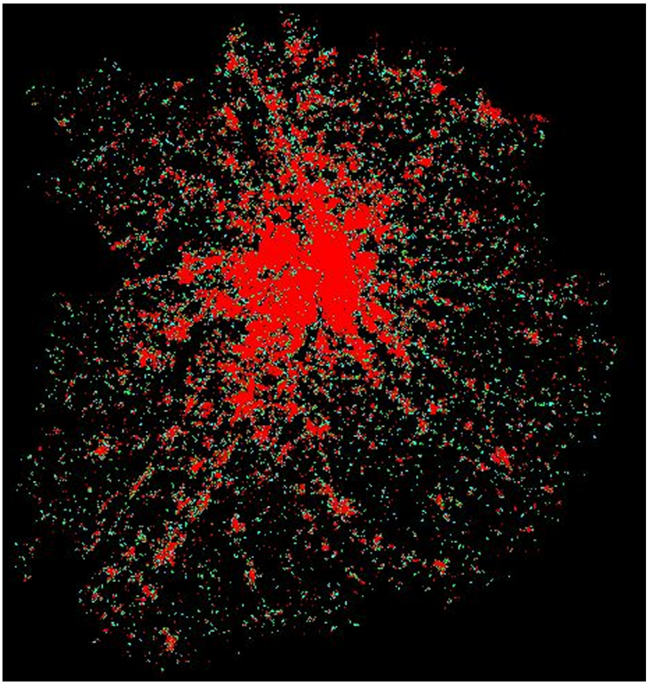


Fig. 5 . Comparison of 2006 urban map with 2006 map simulated using coupled NEDUM–SLEUTH model. The model correctly predicts urban growth (in red), but although the amount of urban extension is correct, its allocation (light blue) does not match the observed situation in 2006 (light green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
comparison of urban structure of the simulated map to the observed one with landscape metrics (Urban area in ha -Area-, Number of urban patches -NP-, Patch density -PD-, Mean distance between patches -MdP-, Cohesion -C-).

Urban map in 2006	Area	NP	PD	C
Observed	59,527	4257	0.5404	97.77
Simulated	60,460	4267	0.5391	98.26

Table 3
Comparison to the observations of the seasonally averaged 2 m air temperatures simulated over Paris centre for (a) the MesoNH atmospheric model (including TEB) (b) TEB with the urban weather generator, (c) TEB without the urban weather generator.

	MesoNH/ observations	Simple weather generator/ observations	Without urban weather generator/ observations
Summer	−0.15 K	0.04 K	−1.15 K
Autumn	−0.22 K	0.60 K	−0.55 K
Winter	−0.21 K	0.91 K	−0.33 K
Spring	−0.67 K	0.16 K	−1.58 K

The statistical scores of the simple weather generator against both observations and the high-resolution atmospheric model are presented, by season, in Table 3. While the simplified urban boundary layer model does not perform as well as the high-resolution atmospheric model, it still reproduces the UHI well, especially in spring and summer (when the UHI is the largest) even though, in winter, the UHI seems overestimated. Overall, this validation shows the improvement brought by the use of a weather generator (instead of nothing) to spatialize the UHI for further energy and comfort studies.

Finally, the TEB was also validated in terms of energy consumption at city scale. At a building scale TEB–BEM has been shown to be capable of estimating the heating and cooling demands for 5 different types of buildings and 2 different climates (Paris and Cordoba) with an accuracy of 5 kWh/m^2/year for heating and 3 kWh/m^2/year for cooling (Pigeon et al., 2014).

The validation at city scale raised a problem of accessibility to energy consumption data, which are commercially sensitive and not generally available. However, some broad-scale statistics are available at the French ministry of ecology. They are available for certain sectors, including residential and office buildings taken together (which is the quantity we aim to simulate) annually for the administrative region that contains the Paris urban area. Given that no other significant town is present in this region, we assumed that these data were representative of Paris and its suburbs. Furthermore, the energy data contains not only statistics for heating and air-conditioning, but also for lighting, hot water and specific electricity use. These are not computed by the model and have to be estimated from the observations. In order to obtain data comparable to TEB–BEM energy consumption, we followed an ADEME (French energy agency) rule of thumb that lighting, hot water and specific electricity use represent approximately 20% of total final energy consumption.

The TEB simulation is initialized, in terms of surface characteristics, from the interpretation of building and urban parameters in the LCZs (map in Fig. 3). Two simulations were run: one without UHI, forced by a rural meteorological station, and one forced by the same station but including the representation of the UHI by the conceptual boundary layer model of Bueno et al. (2012b). We simulated heating (cf Fig. 6) in residential and office buildings (including commercial buildings and hotels). We assumed that in Paris, located in the North of France, air conditioning was only present in office buildings and not in houses or collective buildings (unlike in other regions in the world). As energy consumption in industrial buildings depends on many more factors (e.g. a warehouse can be unheated, while a factory can need a lot of energy for its machinery), their energy consumption was not simulated here. This means that no heating or air-conditioning was computed for grid meshes where usage was industrial.

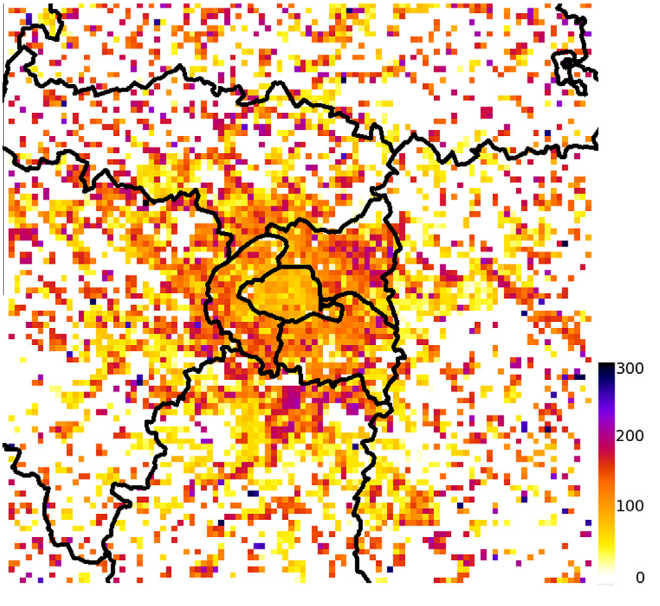


Fig. 6. Energy consumption due to domestic heating in Paris (2008) simulated by TEB. Black lines are administrative boundaries. Inner black line is historic, intra-muros Paris. Resolution is 1 km.

The simulations covered 11 years (from 1998 to 2008) and were compared to data when these were available. TEB, used here at 1-km spatial scale, was able to simulate the energy consumption of the Paris urban area with an error of 5% (using realistic target temperatures for heating (21 °C) and cooling, if any (23 °C)). More importantly, it was able to reproduce the year to year variation of energy consumption (Fig. 7) that was purely due to the response of the system to weather variations. However, the drop for years of low energy consumption seemed overestimated by the model; these were warm years, with less consumption for heating but potentially more for air conditioning. Neglecting all air conditioning in residential areas may explain part of this difference. Unfortunately, there are no data for the 2003 heat wave. While we are aware that there may have been some compensation for errors, this still validates the ability of the model to simulate the energy consumption with the correct order of magnitude and we are confident in its use to assess the relative impacts of different factors or adaptation strategies.

6. Impact assessment

The interdisciplinary approach used here allows a wide range of evolution paths and impacts to be considered and assessed. The indicators used for assessment are based on both the data provided to create the scenarios (results from the participatory approach and data necessary as input to the models) and data simulated by the different models. Some indicators may be a mix of these two. The following subsections present some of the major indicators that we estimated for each adaptation strategy and climate warming scenario.

6.1. Economic and socio-economic indicators

First, a few indicators describing the socio-economic environment of the city are crucial for interpreting the evolution and expansion (or not) of the built-up area. These are derived from the data required to run the models rather than generated by the model simulations. However these data, which are interpreted from other sources (models, expert analyses), must fit the scenarios used to force our models. There are many such indicators but the main ones that impact city development are:

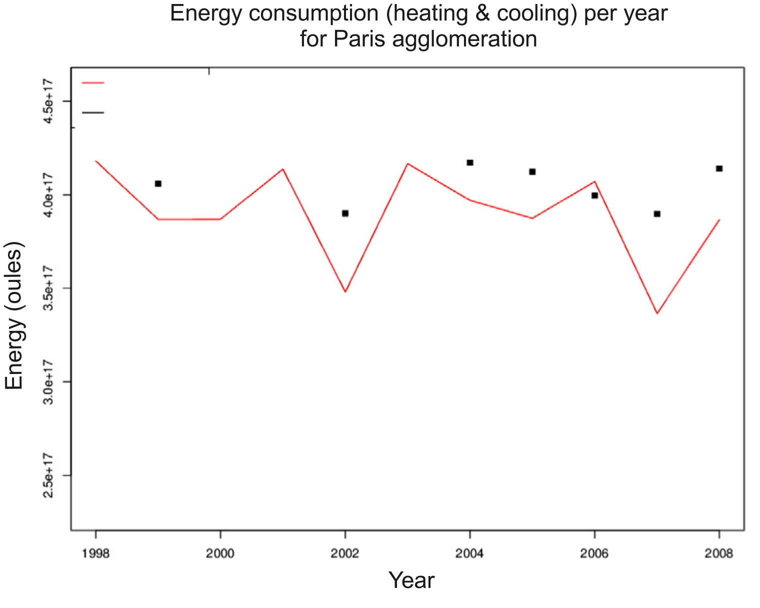


Fig. 7. Energy consumption for buildings (heating and cooling) in Paris urban area.

- The population of the city. This depends partly, but not solely, on the projections of future evolution of the population in this part of the world (nation or continent). It is also strongly dependent on scenarios concerning the welfare of the city in the future: will the city continue to be attractive or will it be in economic crisis (due to over-specialization of local industry, for example). This was implemented in our scenarios by analysing (in the past) the relative difference from the mean national demographic evolution for cities in crisis and attractive cities in France. We then applied the relative difference to derive several future demographic trends.
- The mean revenue of the people in the city. This is linked to the economic context, both national (from global economic models) and local (using a methodology similar to that for the population).
- The intensity and duration of high oil prices (see discussion in Section 3.1).
- The existence (or not) of a global climatic policy among nations. This can influence the price of energy.

Second, there are indicators that describe the way the city will evolve in the future. These are computed from the NEDUM model and include:

- Spatial distribution of the density of population in the urban area: this information is typically at 1-km or even 500-m resolution. It allows the impacts of urban planning strategies on the choice of localization of the inhabitants to be assessed.
- Spatial distribution of the built density (in terms of floor area built). It is at the same resolution as the density of population and allows the size of dwellings to be estimated per occupant. It also is a direct driving factor for the architectural model GENIUS.
- Spatial distribution of the levels of rents. This has a strong influence on (and is influenced by) the choice of the inhabitants to live near the city centre (where dwelling costs are generally higher).
- Time spent and distance travelled in the transport network (public transport or private cars). This is a major urban indicator for urban planners. The modal share of public transport relative to private cars is also an interesting indicator to improve the overall efficiency of the public transport in the city depending on contrasted urban planning strategies.
- Energy and CO_2 emissions by transports in the city. This indicator integrates the information above with scenario-dependent information on technology (vehicle efficiency, proportion of electric vehicles).

6.2. Urban form indicators

The urban expansion models (NEDUM and NEDUM–SLEUTH*) provide indicators on the shape of the city (e.g. for fragmented vs. compact city), while the architectural model GENIUS generates indicators concerning the types of buildings being built in the city. A key indicator is

- The extent and spatial distribution of the urbanized area, which informs us of the overall urban growth.

Other integrated spatial indicators provides measure on the nature of the urban development, such as:

- The number and size of urban patches. This indicates whether the city is dense (small number of large patches of connected urbanization) or fragmented (numerous small patches).
- The type of houses or buildings being built (spatial distribution and integrated values). These are of interest to indicate whether strategies of densification are efficient or not, given the economic environment for example.
- The spatial distribution of the building fraction (as seen from above), of the height of buildings (and its variability in each grid mesh), and of other morphological parameters (e.g. contiguity).
- The spatial distribution of density of vegetation and gardens. Additional indicators, such as the number of inhabitants having a private garden or the number of m^2 of urban vegetation per inhabitant are also useful for urban planners.

6.3. Micro-climate and comfort indices

Our integrated model also estimates weather-related indicators, through TEB. These mainly focus on the Urban Heat Island and human thermal comfort and include:

- UHI intensity (difference between temperature of the city centre and the surrounding countryside at night). It can be averaged over different periods of time (e.g. the season). The daytime UHI is also available.
- The fraction of the population affected by a UHI of at least 1 °C (this threshold is not fixed), which allows us to consider not only the physical parameter but also how many people it affects.
- Human comfort, as assessed by the Universal Thermal Climate Index[10]. This takes account not only of temperature but also of humidity, wind, radiation (both solar, if any, and longwave). The radiation reflected or emitted from surfaces (walls, roads, gardens) is also considered in the index computation. The UTCI has been computed for three types of location: indoors, outdoors in shade and outdoors in direct sunlight.
- The number of hours per day the population spends over a given warm threshold (or under a given cold threshold) of UTCI; this estimates the vulnerability of the population to heat stress, which can then be related to physiological indices (not done here).
- The water needed for watering gardens, parks and greenroofs is also estimated, and related to the runoff of these surfaces. This can give information on the necessity to develop local water storage systems to collect water in winter and irrigate in summer. Roads can also be watered during heat waves (such a strategy is being evaluated experimentally in several cities, for example in Japan and France).

6.4. Energy consumption indicators

TEB–BEM is able to compute energy consumption indicators for heating and air-conditioning including:

- The total energy consumption in the city, or aggregated by building type, or by type of building use (residential, office, commercial).
- The peak power needed. This indicator is important for energy distribution companies, as it helps with the sizing of the energy network and to avoid blackouts.
- The emissions of CO_2 due to residential, office and commercial buildings. The type of energy used, especially for heating, and also how electricity is produced are necessary for this estimate. This information comes from the description of the city and the scenarios. This indicator gives information on the ability to reduce the energy consumption so as to mitigate climate change.
- The variation of energy consumption in winter and summer relative to climate warming and city evolution (in terms of expansion, technology of building and insulation, and behaviour of occupants).

7. Case of Toulouse in 2100: simulations and discussion

The objective in this section is to outline the value of the systemic modelling approach we have developed. Here, we focus on the city of Toulouse using several urban planning scenarios leading to different urban expansions up to 2100 and simple climate warming scenarios: present climate plus 2 °C, 4 °C or 6 °C. We do not present model uncertainty and scenario variability ranges, nor do we provide a full or even partial analysis of strategies for adapting to climate change; this will be done in forthcoming papers. However, the results are instructive and allow some preliminary conclusions to be drawn.

[10] http://www.utci.org.

7.1. Scenarios

Seven systemic scenarios have been simulated. Each describes a pathway for the overall economy, population statistics and attractiveness of the urban area, urban planning, architecture, technology (building and transport), renovation of old buildings, building use and energy use by occupants. Providing the details of all these scenarios, as well as all the simulations and impacts, is beyond the scope of this general paper on the methodology. In the following, we present some results and discuss their links with the relevant aspects of the scenarios. These results have been structured through a collective interdisciplinary analysis by several researchers (from different fields) and the urban planners involved.

7.2. Impacts and discussion

7.2.1. Impact of an economic crisis on population localization within the city

The expansion of the city and the evolution of the density of population between today and 2100 are presented in Fig. 8 for two scenarios. Each scenario follows the same urban planning strategy (business as usual, i.e. with no strong constraint on urbanization), but for two contrasting economic and demographic environments. In one case, the city of Toulouse is still growing and attractive whereas, in the second, a crisis around 2040 tends to stop the arrival of new inhabitants. The crisis scenario leads to a less extended city (as expected). However, the crisis also has an impact on the location of the people within the city: people move from the centre towards the suburbs, because of the excessive price of dwellings in the centre compared to their income. Conversely, in the attractive city case, the city centre is one of the most attractive places.

7.2.2. Impact of an urban planning strategy on city expansion and unexpected effects

Our systemic modelling approach also simulates the influence of different urban planning strategies. For example, a strategy that is employed to reduce energy consumption (especially from transport) is to promote a compact city (or densify an existing city). One way to achieve this is to implement a 'green belt' around the existing city, where it will not be possible to build so that the city extent becomes constrained.

One such green belt scenario was simulated and compared to the 'business as usual' urban planning scenario for which the city sprawls without many constraints. During the first half of the century, the green belt has the expected effect; the city becomes more densely occupied and travel times reduce within the city compared to the sprawl case. But what happens after 2050 if the population continues to grow? The cost of housing inside the green belt becomes so high that people prefer to live outside it ('leapfrogging' effect), at the cost of increased travel time. By 2100, for the same population increase, the distance between home and work within the city increases by 122% compared with today for the green belt case, while it increases by 'only' 93% for the sprawled city. The green belt policy, if left unchanged for 100 years, has had a counter-productive effect. This does not mean that a green belt policy should not be implemented now but it does suggest that, if a city continues to be attractive and grow, it should be adapted, and maybe become even more binding, in the future. This would require even more coordination among the planning authorities within the area.

The systemic approach explores the limits of some policies in the very long term, and can shed some light on when they could appear depending on population scenarios.

7.2.3. Urban forms: the need for anticipation

Two scenarios with the same population evolution and same policy for overall urban planning were simulated. They differ only in the choice of the type of local urban form (expressed in the LZC class) that was favoured. In one scenario (scenario 2 in Fig. 9) small collective buildings are built from now for intermediate built densities, while in the other (scenario 1) this is the case only after 2040, individual houses still being built until then. Then, in both scenarios, a major crisis occurs in 2040, limiting the population growth. The collective buildings policy proves to be inefficient when taken after 2040, because the renewal of buildings is too slow after the crisis.

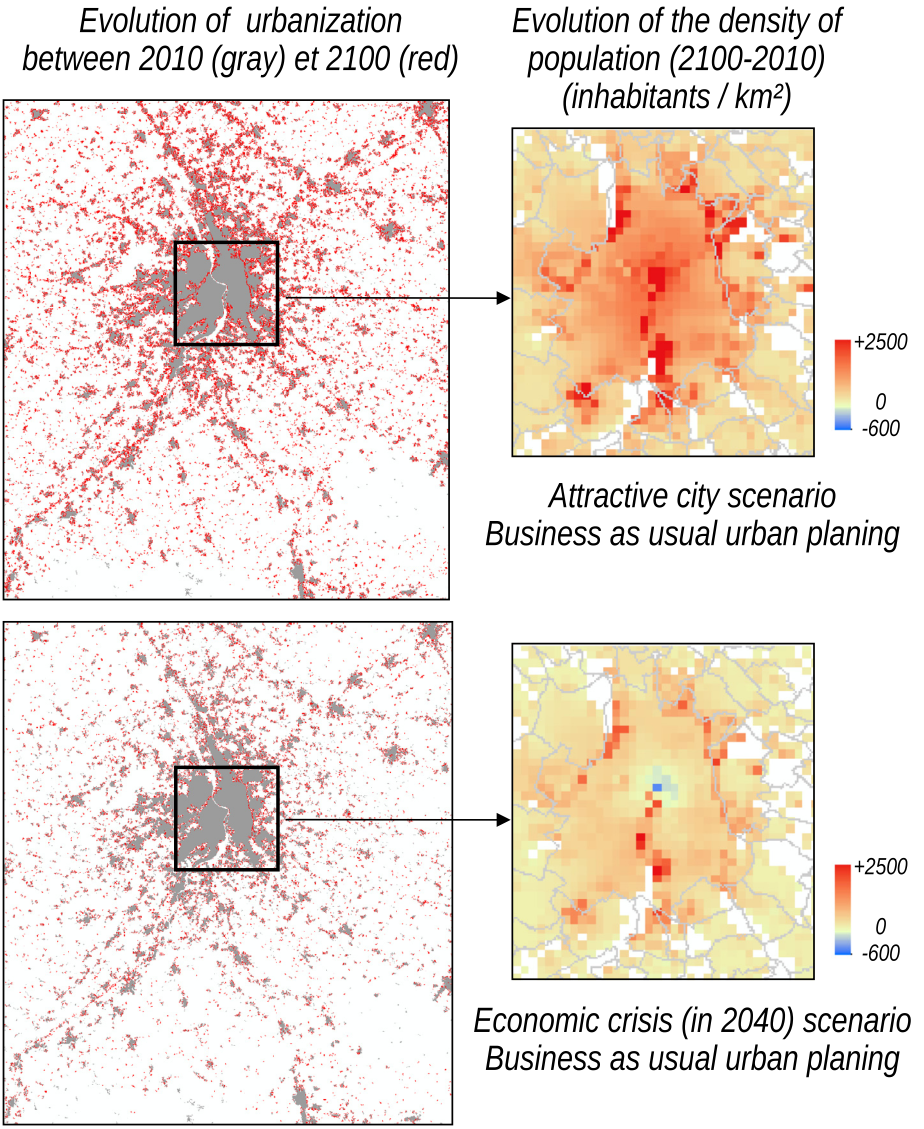


Fig. 8. Possible situation in 2100 of Toulouse urbanization (left) and population density in the city centre (right) following a 'business as usual' urban planning strategy in a scenario of an economically attractive city (top) or a scenario of economic crisis (bottom).

7.2.4. Urban Heat Island

As is well known, the magnitude of the Urban Heat Island is correlated with the city's population size. This relationship is captured by our simulations; the UHI of the attractive city with 'business as usual' urban planning and technology scenarios increases by up to 1.5 °C on average in summer compared to today's city (950,000 households instead of 550,000 today).

However, other effects seem to modulate this.

Renovation of buildings and modification of insulation practices (with insulation on the outside of the wall instead of inside) limits the heat that can be stored in the urban fabric by day. Also, the use of lighter coloured paints for roofs reduces solar energy absorption. Together, these building

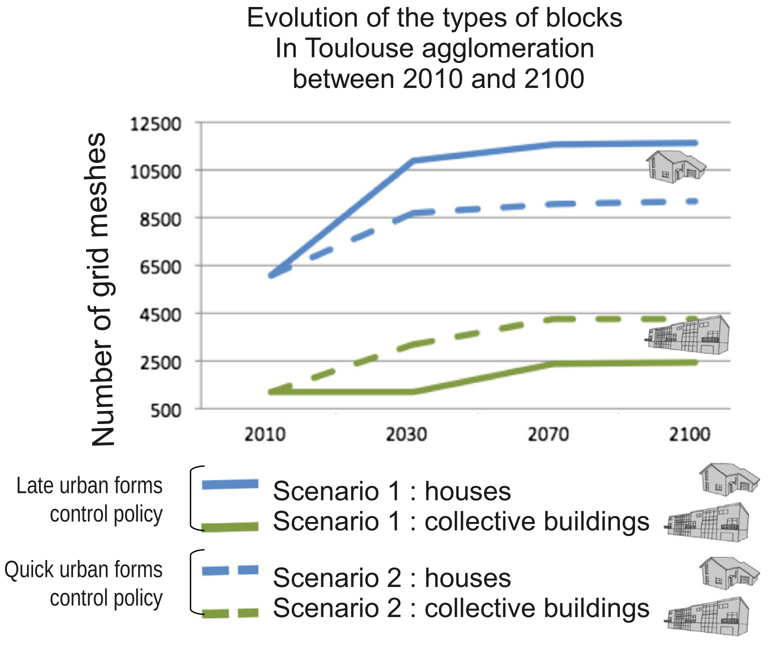


Fig. 9. Possible evolution during the 21st Century of two types of buildings (houses and collective buildings) for scenarios with a rapidly implemented or delayed urban forms control policy.

modifications reduce the UHI by 0.5 °C for Toulouse. The habits of the population also influence the UHI. Measures to decrease the heating target temperature by 2 °C decrease the UHI by a couple of tenths of a degree. The greening of available spaces within the city (for example open spaces, pavements, and car parks) decreases the UHI further, especially in summer, but not necessarily everywhere. As the city centre of Toulouse is already very dense, there is very little room for vegetation and the UHI is not attenuated so much as in the suburbs (almost 1 °C cooler in summer than for a mineral city).

7.2.5. Energy consumption and climate warming

Energy consumption simulations are performed by TEB, which interacts with the simulated city scale UHI. Here, we present only those results relative to the present city case, in order to highlight broad tendencies on a few indicators. The energy values have been normalized by floor area (per square metre) per year for both heating and cooling, to remove the effect of number of inhabitants (or equivalently the total built area of floors) (Fig. 10).

The first important conclusion about energy is that the main levers to decrease the (normalized) energy consumption are renovation of the buildings and, even more, the way of life of the inhabitants in their homes or the way companies use their offices.

The scenario without any renovation does not permit significant energy reduction, as the many efficient buildings built in the future (between now and 2100) will not be able to mask the energy waste in older buildings. When buildings are moderately renovated (1.5% of buildings renovated per year, i.e. the current rate), heating energy use is approximately halved. By contrast, the cooling demand does not change much, as it is primarily driven by incoming solar radiation in homes and offices.

When people adopt more virtuous ways of using their homes (heating to 19 °C instead of 21 °C, cooling to 26 °C instead of 23 °C), then the heating demand is reduced by 30% and the cooling demand is reduced by 66%.

The different urban adaptation strategies and faster renovation rates may not seem to impact the normalized energy consumption significantly (although they modify the UHI). However, this is probably an artefact due to the scenarios chosen, each of which prescribe well insulated buildings

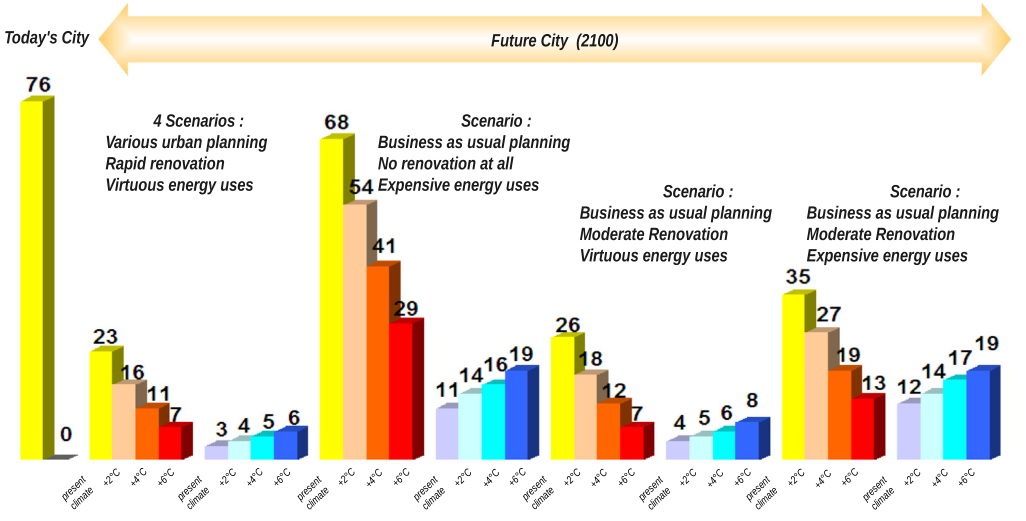


Fig. 10. Normalized energy consumption (in kWh/m^2 of floor/year) for domestic heating (warm colours) and air-conditioning (cold colours) for present-day urban area of Toulouse (left) and several projections for the evolution of Toulouse depending on different scenarios. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and virtuous uses by 2100. Because of this, the buildings are less sensitive to the weather outside (and heating is less necessary). For shorter time horizons (to 2030 or 2050), the urban forms may have more impact as buildings will not all have been renovated. Also, people may never adopt virtuous energy uses in their dwellings. So further work is needed (and ongoing) in order to analyse the impact of urban forms more finely for shorter time horizons.

The second conclusion is that, for a city in a temperate climate like Toulouse, climate warming will lead to an overall decrease the total energy consumption due to buildings. This comes from the more rapid decrease in the need for heating than the increase in need for air conditioning. However, this will have to be discussed in terms of what type of energy is used. While heating can be provided by electricity, fuel oil, gas or wood, air-conditioning needs electricity. So, the peak of electricity distribution may appear in summer instead of winter for even small to moderate climate warming. For some scenarios, even the total amount of energy used may be larger in summer than in winter; this may require a reconfiguration of the electricity production system over the long term.

8. Conclusions

The complexity of the urban system seems extreme. This leads to difficulties in anticipating the benefits or costs and drawbacks of present and future adaptation strategies to climate warming. However, we have shown here that some of this complexity can be taken into account if an interdisciplinary approach is followed. Furthermore, as the interactions between processes are many and not always intuitive, numerical modelling is well suited to the task.

In this work, we have coupled socio-economic, geographical, architectural, building energetics, urban climate and atmospheric models. The architectural model was specifically developed for this study. Coupling these models not only allows us to provide a better description of the processes that link elements of the urban system, but also permits an interdisciplinary analysis of the impacts for a very broad range of topics (monetary costs, population distribution in the city, architectural forms, energy, micro-climate, anticipation of side effects of adaptation measures, definition of the requirements to ensure adaptation measures achieve the expected performance levels, and so on).

One of the preliminary findings of this paper is that, even for similar impacts (total or instantaneous energy demand) the relative influences of city evolution and climate change varies depending on the specific impact we focus on. Another finding is that it is important to consider the UHI if the energy demand is to be accurately reproduced in cities and to take it into account in the operational estimation of building energy demands.

Our next step will be to evaluate a large number of strategies for adapting to climate change using the systemic modelling approach. This will require the development of mixed backcasting and forecasting scenarios within a prospective approach (Houet et al., 2010; Marchadier et al., 2012) that force or constrain the various models. Different climate change scenarios will also be used. These further studies will allow each adaptation strategy to be assessed in a context of uncertainty (not only climatic but also economic and technological), using numerous indicators and allocating estimations of uncertainties to them. The systemic modelling approach draws advantage from the methodological interactions between the creation of the scenarios and the definition of the coupled modelling platform. As a result, it allows the exploration of a wider diversity of urban futures than exclusive model-driven approaches can.

Moreover, this approach may favour the participation of those most concerned by the results in defining new scenarios according to land system theory (Kok et al., 2004; Dearing et al., 2007; Turner et al., 2007; van der Leeuw et al., 2011). For example, it appears that some urban planning strategies, such as green belts, can be efficient and achieve their goals in the short term (the next few decades) but produce counter-intuitive and opposite impacts in the long term if the city continues to grow. So, while such strategies could be implemented now, this underlines the need to prepare others for the future. The decision and urban policy making systems may need to be modified in order to be able to create and set in motion more binding policies if necessary. Anticipation is also necessary, as what will be built in the next decades may still be unchanged by the end of the century.

Changes to energy demand in the future may lead to issues for energy production units that are less efficient in summer, such as nuclear or gas power plants, or wind turbines. However, this issue could be anticipated, using urban forms that can be more efficient at producing renewable energy, for example solar energy. This will also be tested in our scenarios and modelling in forthcoming studies.

Some adaptation measures do impact the urban landscape. The massive installation of solar collectors, the implementation of wind turbines, the modification of the radiative properties of walls, roofs and street surfaces, and the development of green areas change people's perception of the city. The acceptability of such modifications by citizens and by tourists has to be addressed. This is one of the elements to be taken into account by decision makers, together with economic, technical and maintenance considerations. A measure that would be efficient from a technical point of view but that would decrease the attractiveness of a city could be counterproductive for the local economy. A measure with lower effectiveness but that would enhance attractiveness could be positively assessed.

Changes in human behaviour seem to be a very potent lever for adaptation in cities. In addition to the elements presented above, the way people behave in terms of energy use, and of their dwelling or office in general, may strongly modify the energy consumption in the city. People may set different, more virtuous, target temperatures for heating and air-conditioning. They may even use features of their house to avoid or limit the need for air-conditioning. However, these types of behaviour will probably differ according to age or socio-economic status. Building renovation is also a key trigger, and often depends of the will of the occupants to carry out adequate work in their house or apartment.

Future work will also have to focus on such questions. Dealing with these questions reinforces the need for the interdisciplinary approach we advocate here.

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