Urban dynamics modelling : application to economics assessment of climate change

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Économie

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Modélisation des dynamiques urbaines,
application à l'analyse économique du changement climatique

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Abstract

Because they are home to more than half of the world population, and because most of the world economic activity takes place within them, cities are at the forefront of global environmental issues. Land use planning, urban transport and housing policies are now recognized as major tools for the reduction of both greenhouse gases emissions and vulnerability to climate change impacts. So far, however, how to use these tools efficiently remains unclear. At least three main difficulties explain this, and play a key role in urban climate policies analysis. First, urban climate policies are also not developed or implemented in a vacuum; they interact with other policy goals, such as economic competitiveness or social issues, giving rise to both synergies and conflicts. Second, inertia is a key factor when designing optimal climate policies: structural modifications in cities occur slowly over a long time horizon. Some immediate actions are required if cities are to be adapted to a different climate or to help reduce greenhouse gases emissions within a few decades. Third, the evolution of a city depends on several external factors, on which local policy-makers do not generally have much influence: demographic, socio-economic, cultural, political and technological changes will play a major role. This uncertainty has to be taken into account, and climate policies have to be robust against future possible global evolutions is important. These three difficulties are not, however, impossible to overcome, and we will illustrate how integrated city modelling can help address these issues.

Keywords

Urban modelling, climate change, adaptation, mitigation

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Résumé en français

Parce qu'elles concentrent plus de la moitié de la population et l'essentiel de l'activité économique mondiales, les villes sont des acteurs majeurs des problématiques environnementales globales. Les politiques de transport, d'urbanisme et de logement sont ainsi reconnus comme des moyens nécessaires et efficaces d'action pour réduire les émissions ainsi que pour réduire la vulnérabilité aux impacts du changement climatique. Jusqu'à présent, malheureusement, il n'y a pas de consensus sur ce qui doit être fait, et encore moins sur comment le faire. Trois difficultés, au moins, expliquent cela. Tout d'abord, les politiques climatiques interagissent avec les autres objectifs des politiques urbaines, comme la compétitivité économique ou les problèmes sociaux, entrainant des synergies et des conflits. Ensuite, les inerties sont un facteur-clef à prendre en compte : les modifications structurelles des villes s'opèrent très lentement. Si l'on veut que les villes soient adaptées au climat de la fin du XXIème siècle, il est indispensable de commencer à agir dès maintenant. Enfin, les effets des politiques urbaines dépendent de nombreux facteurs exogènes, et inconnus au moment où la décision doit être prise : les changements démographiques, socio-économiques culturels politiques et technologiques vont jouer un rôle majeur. Ces trois difficultés ne sont cependant pas insurmontables, et nous illustrerons comment une modélisation intégrée peut permettre de répondre à une partie de ces problèmes.

Mots-clef

Modélisation urbaine, changement climatique, adaptation, mitigation

Résumé long en français

Parce qu'elles concentrent plus de la moitié de la population et l'essentiel de l'activité économique mondiales, les villes sont des acteurs majeurs des problématiques environnementales globales. Elles le sont notamment dans le cadre de la réduction des émissions de gaz à effet de serre, et de la réduction de la vulnérabilité au changement climatique et aux risques naturels. Les interactions d'une ville avec l'environnement sont complexes, et régies par de nombreux facteurs. L'un d'entre eux, cependant, a un statut tout à fait particulier : son organisation spatiale, parce que celle-ci joue un rôle prépondérant dans l'intensité et dans l'organisation des flux qui caractérisent le fonctionnement de la ville, et parce que celle-ci détermine l'exposition aux aléas naturels.

Les politiques de transport, d'urbanisme et de logement sont ainsi reconnues comme des moyens nécessaires et efficaces d'action pour réduire les émissions, ainsi que pour réduire la vulnérabilité aux impacts du changement climatique . Il n'est donc pas surprenant que la réflexion sur l'évolution attendue de la structure spatiale des villes soit au cœur de nombreuses réflexions prospectives sur l'adaptation et l'atténuation du changement climatique, notamment au sein du GIEC, de la Banque Mondiale, ou de l'OCDE. Jusqu'à présent, malheureusement, il n'y a pas de consensus clair sur la manière d'utiliser ce levier efficacement. Dans ce document, notre thèse est que trois raisons, au moins, expliquent cela, et jouent un rôle clé dans l'analyse des politiques climatiques urbaines.

Tout d'abord, l'inertie est un facteur déterminant dans la définition de ces politiques. En effet, une fois construite, une ville n'évolue que très lentement. En Europe, il a ainsi fallu des siècles pour parvenir à la structure des villes actuelles, et comme les bâtiments ont généralement des durées de vie variant de 50 à plus de 100 ans, nos choix actuels conditionnent en grande partie les émissions et la vulnérabilité urbaines tout au long du siècle. Si l'on veut que les villes soient adaptées au climat de la fin du XXIème siècle, et si l'on veut réduire significativement les émissions de gaz à effet de serre d'ici quelques décennies, il est indispensable de commencer à agir maintenant, et à modifier la conception des bâtiments et les stratégies de planification urbaine.

Deuxièmement, l'évolution d'une ville dépend de nombreux facteurs exogènes, et inconnus au moment où la décision doit être prise : les changements démographiques, socio-économiques, culturels, politiques et technologiques vont jouer un rôle majeur. Par exemple, le succès de stratégies visant à réduire les émissions liées aux transports est dépendant des évolutions futures des prix énergétiques, et des technologies qui existeront à l'avenir. Cette incertitude doit être prise en compte, et les politiques climatiques doivent pouvoir être robustes face à celle-ci. Nous affirmons qu'il est important que la planification urbaine soit faite dans un esprit de prospective intégrant cette incertitude, et nous proposons ici un exemple d'approche basée sur la construction de scénarios.

Troisièmement, les politiques climatiques urbaines ont un impact sur les autres ob-

jectifs des décideurs urbains, comme la compétitivité économique, ou la gestion de problèmes sociaux. Ces interactions peuvent conduire à des arbitrages à réaliser, lorsque ces objectifs s'opposent, ou bien à des synergies lorsqu'une mesure a des effets secondaires positifs. Des conflits et des complémentarités existent aussi entre politiques d'adaptation et d'atténuation, car celles-ci sont souvent basées sur les mêmes outils. Ces problèmes d'acceptabilité sociale et politique, et d'efficacité, sont importants, et doivent être pris en compte dans l'analyse des politiques climatiques urbaines. Nous montrons ainsi qu'intégrer différents objectifs dans un cadre cohérent (ce que à quoi on réfère parfois par l'expression anglaise « mainstreaming ») peut permettre de concevoir des politiques plus efficaces et plus acceptables.

Nous allons présenter quelques outils permettant de s'attaquer à ces problèmes. Les modèles prospectifs, bien qu'ils soient une description très simplifiée de la réalité, avec des hypothèses qui restreignent les possibilités qu'ils peuvent explorer, sont un outil efficace pour créer des scénarios prospectifs et analyser des rétroactions complexes. En permettant aux acteurs des problématiques climatiques de mieux comprendre les principaux mécanismes et interactions en jeu, ils constituent une base utile pour la discussion. Nous allons présenter ici un tel modèle, NEDUM-2D, et allons l'utiliser pour illustrer dans quelle mesure il peut aider à résoudre les problèmes que nous avons soulevés.

Développer des modèles d'aide à la décision pose des difficultés techniques : les modèles doivent prendre suffisamment de mécanismes pour pouvoir analyser la réalité. D'un autre côté, cependant, ils doivent rester suffisamment simples pour que leurs conclusions et leur domaine de validité restent clairs à leurs utilisateurs, c'est-à-dire qu'il faut éviter un effet de « boîte noire ». Les modèles doivent donc être conçus et définis en fonction de la question à laquelle ils doivent apporter des éléments de réponse. En ce qui concerne les questions climatiques, les modèles urbains existants ne sont pas suffisants : souvent, ils sont trop complexes ne prennent pas en compte des mécanismes nécessaire dans l'étude des problèmes climatiques. C'est pourquoi nous avons décidé de développer notre propre modèle : NEDUM-2D.

Un tel modèle est un travail qui ne peut être achevé : il doit être constamment complété, raffiné, ou parfois simplifié pour correspondre aux besoins, questions et certitudes de ses utilisateurs. Ce que nous proposons ici n'est pas un outil permettant de résoudre définitivement out les problèmes climatiques urbains, mais c'est un premier pas dans le développement d'un cadre permettant se s'attaquer à certains de ces problèmes.

La partie I de cette thèse est une introduction qui développe les idées présentées ici. Elle présente dans quelle mesure les problèmes climatiques sont importants pour les décideurs urbains. Le premier chapitre expose les enjeux liés à la réduction des émissions de gaz à effet de serre : il met en évidence pourquoi les émissions urbaines ont une importance particulière dans le débat général sur l'effet de serre, et en quoi les politiques urbaines peuvent etre efficaces. Le deuxième chapitre expose les enjeux liés à la vulnérabilité des villes aux impacts futurs du changement climatique, et aux politiques de réduction de cette vulnérabilité. Basé sur ces deux revues, le troisième chapitre explique la thèse de ce document, et résume les principaux résultats qui seront obtenus dans les parties II et III.

La partie II présente la modélisation que nous avons adoptée. La modélisation intégrée des villes vise à fournir une description quantifiée des interactions entre différents processus urbains, et peut décrire l'influence d'évolutions globales sur ces processus. C'est un outil efficace pour répondre aux problèmes soulevés dans le chapitre 3. Cepen-

dant, l'utilisation de tels outils pose des problèmes spécifiques, que chaque chapitre de cette partie va examiner. Le Chapitre 4 fait tout d'abord une brève revue des approches et des théories existantes pour modéliser les villes. Les chapitres suivants présentent et expliquent les modèles que nous avons conçus. Notre approche est itérative. Partant du modèle standard développé par l'économie urbaine, nous introduisons progressivement des mécanismes additionnels pour répondre à des problèmes de complexité croissante.

Enfin, la partie III explore dans quelle mesure les modèles que nous avons conçus peuvent répondre aux questions que nous avons soulevées dans la partie I, et peuvent aider à concevoir ou à évaluer des politiques locales d'atténuation des émissions de gaz à effet de serre et d'adaptation face aux conséquences du changement climatique. Cette partie est basée sur trois articles de recherche. Avant chacun d'entre eux, un brève introduction explique le contexte et présente les principales conclusions.

Contents

Summary

Because they are home to more than half of the world population, and because most of the world economic activity takes place within them, cities are at the forefront of global environmental issues, among which greenhouse gas emissions reduction, and vulnerability to climate change and natural hazards. Interactions between a city and its environment are complex, and influenced by numerous factors. One of them, however, plays a special role: the urban geographical form, i.e. the spatial repartition of people and assets because it plays a major role in shaping the fluxes[2] that characterize the life of a city, and in constraining the infrastructure[3] locations, types and shapes.

Land use planning, urban transport and housing policies are now recognized as major tools for the reduction of both greenhouse gases emissions (climate change "mitigation") and vulnerability to climate change impacts ("adaptation" to climate change). It is therefore not surprising that reflexions on city spatial structure are at the heart of many prospective studies on climate change adaptation and mitigation, for instance in IPCC, OCDE, UN-Habitat or the World Bank[4]. So far, however, how to use efficiently most of these tools remains rather unclear. In this work, our thesis is that at least three main difficulties explain this, and play a key role in urban climate policies analysis.

First, inertia is a key factor when designing optimal climate policies: structural modifications in cities occur slowly over a long time horizon. Some immediate actions are required if cities are to be adapted to a different climate or to help reduce greenhouse gases emissions within a few decades. We claim that it is especially urgent to start changing building design and urban planning habits.

Second, the evolution of a city depends on several external factors, on which local policy-makers do not generally have much influence: demographic, socio-economic, cultural, political and technological changes will play a major role. For instance, success of strategies aiming at reducing transport related energy consumption is dependent on future transport prices. This uncertainty has to be taken into account, and climate policies have to be robust against future possible global evolutions. We affirm that urban planning needs to be done in a "prospective" mindset, considering the uncertainty on many drivers of urban dynamics, and we propose a scenario-based approach to do so.

Third, urban climate policies are not developed or implemented in a vacuum; they interact with other policy goals, such as economic competitiveness or social issues. Urban policies have multiple goals, such as enhancing the quality of life and the city's

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[2]of people, goods, energy, water, information etc.

[3]transport infrastructure, buildings, plants etc.

[4]cf. Van Ypersele (2007), Kamal-Chaoui and Robert (2009), UN-Habitat (2011) and Hoornweg et al. (2011a).

economic competitiveness by means of affordable housing and office space, amenities, and efficient public services (from good schools to rapid transportation). Urban policies also have social objectives aimed at poverty and social segregation issues, safety and security, and public health. They have local environmental goals as well, such as reducing air and water pollution and preserving natural areas. In addition to this long list of goals, urban policies now face new challenges from climate change. Environmental policies can result in positive feedback with respect to economic and social issues. Conflicts among different policy goals can also take place leading to trade-offs and implementation obstacles. Social and political acceptability issues are important and the political economy of climate policies needs to be investigated. We show that integrating various goals in a consistent decision-making framework (what is sometimes referred to as "mainstreaming") allows for more efficient and acceptable policies.

We will present some tools which can help solve these problems. Prospective studies that explore various possible evolutions of global variables and their local consequences on cities are for instance especially useful to design the best policies. Quantitative models, although they are highly simplified descriptions of reality, with hypotheses restricting the possibilities they can explore, are an efficient tool to create such prospective scenarios and analyze complex feedbacks. By enabling decision makers and stakeholders to understand the main mechanisms and interactions between variables, they can create a basis for policy discussion. We will present here such a model, NEDUM-2D, and use it to illustrate to what extent it can help address previous issues.

Developing models which can help policy making raises technical difficulties: models have to include the main processes and mechanisms, to be able to properly analyze the reality. At the same time, however, they have to be simple enough so that their conclusions and their validity remain clear to its users, to avoid the "black-box"effect: models have to be designed based on the question they are trying to answer. For climate questions, existing integrated urban models are not sufficient: they are often too complex, and at the same time often do not take into account mechanisms relevant for environmental issues. We therefore decided to develop our own model, NEDUM-2D.

Such a model is a never-ending work: it should be always completed, refined, or sometimes simplified to meet needs, questions, and beliefs of its users. What we propose here is not a definitive tool to solve all urban climate problems, but it is a first step towards the development of a framework which may enable to address some issues.

Part I is an introduction that develops the ideas presented here. It presents to what extent climate issues are of relevance for urban decision-makers. The first chapter deals with mitigation issues : it highlights why urban greenhouse gases emissions matter in the broader global warming debate, and how urban policies act on them. The second chapter looks into detail at cities vulnerability to climate change impacts, and at policy options to reduce this vulnerability. Based on these reviews, Chapter 3 will explain the thesis of the present document, and will sum up the main findings we will present in Parts II and III.

Part II explains the modeling approach we have followed. Integrated city modeling (ICM) aims at giving a quantitative description of the interaction between different urban processes, and can describe the influence of the evolution of global parameters on these local processes. It is therefore an efficient tool to address issues described in Chapter 3. Using ICM poses however specific problems, to which each chapter of this Part aims to answer. Chapter 4 does, first, a brief review of existing approaches and theories for city modeling. It defines more precisely what exactly means "City

Modeling", and its challenges, advantages and limitations. Next chapters present and explain the models we have designed. Our approach is iterative. Starting from the classical urban economy model, we introduce progressively additional mechanisms to answer increasingly complex problems.

Part III explores to what extent the models we have designed can answer the questions we have raised in Part I, and to what extent it can give some useful information for the design and assessment of mitigation and adaptation policies at local scale. This part is based on the text of three research articles (Viguié and Hallegatte, 2011; Viguié et al., 2011; Viguié and Hallegatte, 2012). Before each of them, a short introduction explains the context and highlights main conclusions.

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Part I

Introduction: Cities and Climate Change

Chapter 1

Cities and greenhouse gases emissions

> *It is particularly ironic that the battle to save the world's remaining healthy ecosystems will be won or lost not in tropical forests or coral reefs that are threatened but on the streets of the most unnatural landscapes on the planet.*
>
> Worldwatch Institute, 2007p. xxiv. , cited in UNFPA, 2007

We live today in an urbanizing world, and cities are already responsible for an important share of global greenhouse gas emissions. Understanding how urban lifestyles impact GHG emissions is therefore of foremost importance to reach a world low-carbon development pathway.

This chapter first presents main figures concerning cities and present urbanization trends (Section 1.1). It then considers issues related to the definition of "urban" GHG emissions, and presents major figures of available assessments (Section 1.2). Possibilities of emission abatement depend on the origin of these emissions: Section 1.3 breaks down urban emissions in several sectors and briefly presents some abatement options. Finally, Section 1.4 highlights the particular role played by a variable: the urban shape, and explains why urban decision-makers can have a determinant role in global emission reduction policies.

1.1 An urbanizing world

Cities are now home of more than half of the world population (Fig. 1.1). While the urban population represented just a small fraction of the world population until the middle of the 19th century, it suddenly increased during the industrial revolution, first in Europe and then in the rest of the world. This transfer is more or less complete in developed countries, but in developing countries it is currently occurring very fast. The threshold of over 50% of the world population living in cities has just been passed and the figures are still rising (unless there is a note to the contrary, all figures quoted are from UNPD, 2008).

Four fifths of North Americans and 90% of Belgians, Islanders and Israelis live in towns (see, for example, Huriot and Bourdeau-Lepage, 2009 for a more detailed discussion of this point). The proportion of urban dwellers is lower in the less-developed
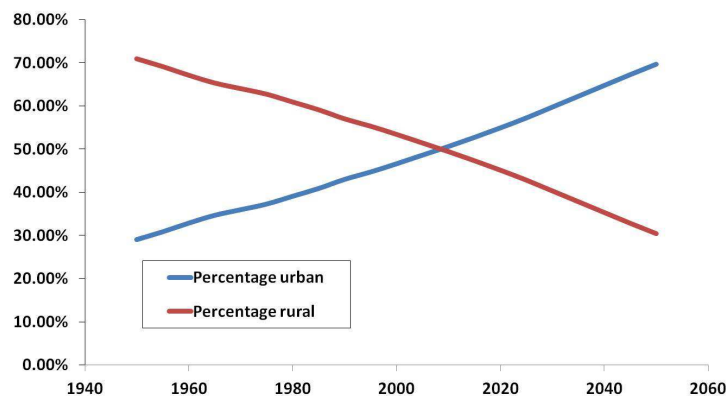
Figure 1.1: People Living in Cities, as a percentage of world population. Source: UNPD, 2008

countries but is still close to 44% of the population and is growing constantly; it is estimated that 50% of their population will be urban by 2020.

When this is viewed in the light of an increasing world population, this increase in urban dwelling is leading to a veritable explosion in the number of world-wide cities inhabitants. The United Nations estimates that by 2050, the world's urban population will almost double from 3.4 billion to 6.3 billion, representing most of the global population growth over that time.

The pace or urbanization in the world today is unprecedented, with a near quintupling of the urban population between 1950 and 2011. There are everyday 190,000 more urban dwellers on the planet. This is the equivalent of the population of Munich, Stockholm or Lyon urban area added every week. The speed of this growth has never been matched in history. It look 130 years for London to rise from one million to 8 million inhabitants but it only took 45 years for Bangkok, 37 for Dakar and 25 years for Seoul to see the same increase in population (UN-Habitat, 2004).

The fastest rates of urbanization are currently taking place in the least developed countries, followed by the rest of the developing countries – comprising three quarters of the world's urban population. From now until 2020 almost all world demographic growth will take place in the countries of the South, their urban populations growing from 2 to 4 billion out of a total population which will increase from 5 to 7 billion. Housing 2 billion inhabitants means building the equivalent of seven new cities of 10 million inhabitants every year, i.e. seven times Shanghai or Jakarta or ten times London. In China alone, it is expected that, until 2035, the urban population will increase by around 315 million people (UNPD, 2010), a figure higher than current total US population (312 million in 2011, according to US census bureau).

This growth is not uniformly distributed among cities. It is expected (UNPD, 2008) that the number of very large cities (conurbations of over 10 million inhabitants, like Paris conurbation for example) will grow from 19 to 26 by 2025 (Fig. 1.2), two thirds of them will only experience modest population growths (less than 2% a year). At present these represent 9% of the urban population and by 2025 they will represent about 10%. By 2025 almost half of new urban dwellers will be housed in towns of less than 500,000 inhabitants, towns which already, today, are home to over 50% of the world urban population.

Another important fact to note is that the present growth in cities is more and more land hungry (Angel et al., 2005); average urban density (the number of inhabitants
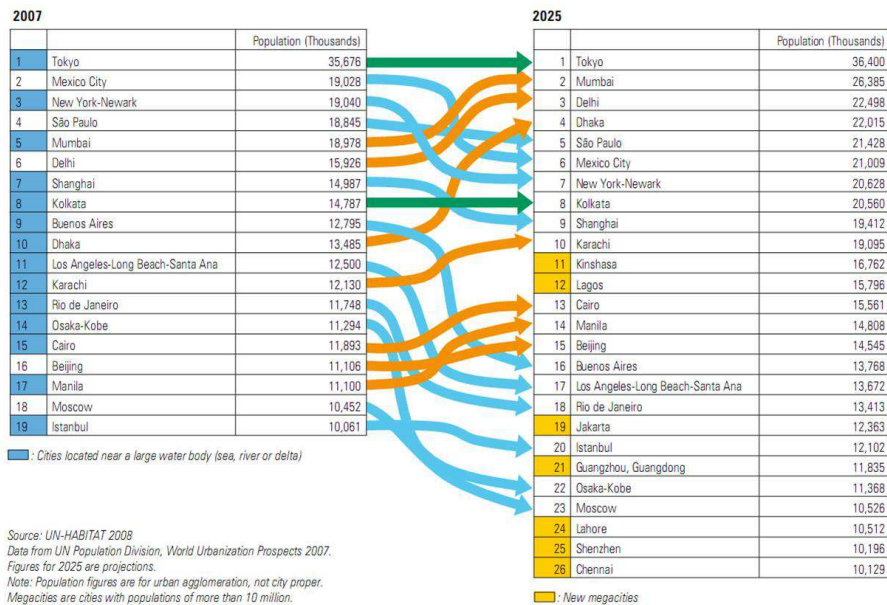
Figure 1.2: The world's megacities, 2007 and 2025. Source: UN-Habitat, 2008

per square kilometre of built surface) has been diminishing for two centuries due to improvements in modes of transport. Between 2000 and 2030, the world's urban population is expected to increase by 72 per cent, while the built-up areas of cities of 100,000 people or more could increase by 175 per cent . In the past decade, the average density of towns in developing countries has decreased by 1.7% per year and that in developed countries by 2.2% per year (for more information see the notes to Chapter 4 of UNFPA, 2007). If current trends are maintained during the next 20 years built surface (green areas excluded) of towns of 100,000 inhabitants and more, which covered in 2005 an area the size of Morocco is set to triple. The built surface of developing countries cities with more than 100,000 inhabitants will be multiplied by 3 and will reach 600,000 km2 (equivalent to the surface of France) while the built surface of developed countries cities will be multiplied by 2.5 and will reach 500,000 km2 (the surface of Spain).

1.2 A global perspective on GHG emissions

Defining cities emissions or energy consumption raise several issues. First, there is no globally accepted definition of the boundaries of an urban area or city, which often leads to figures based on different references when considering figures disclosed by different countries (Hoornweg et al., 2011a). Further than this, another issue is that the scope of the activities to be taken into account is also not consensual. Indeed, one must decide whether energy consumption or emissions are the "responsibility" of those who directly produce them or those whose consumption drives their production. The main issue is to what extent "*upstream*" consumption and emissions or "*embodied*" consumption and emissions, which are associated with extraction, production, transportation of products, or services used by the city (Satterthwaite, 2008; Hoornweg et al., 2011b,a),

should be included. The World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) introduced three scopes that should be considered for calculating greenhouse gas emissions, and which are listed in Tab. 1.1. All the following figures are either given from the perspective of the location of final energy consumption (scope 2), or from the perspective of the standard produced by UNEP, UN-HABITAT and the World Bank, which includes all emissions produced within a city, major emissions from consumption within a city, and major upstream emissions that are attributable to city residents (between scope 2 and 3).

	Definitions	Examples
Scope 1	All direct emissions sources located within the geopolitical boundary of the local government.	Use of fuels such as heavy fuel oil, natural gas or propane used for heating.
Scope 2	Indirect emissions that result as a consequence of P activity within the jurisdiction's geopolitical boundary j limited to electricity, district heating, steam and cooling consumption.	Purchased electricity used within the geopolitical boundaries of the jurisdiction associated with the generation of GHGs at the power plant.
Scope 3	All other indirect and embodied emissions that occur as a result of activity within the geopolitical boundary.	Methane emissions from solid waste generated within the community which decomposes at landfills either inside or outside of the community's geopolitical boundary.

Table 1.1: Emissions scope for cities. Source: UN-Habitat, 2011, after ICLEI and Australian Government Department of Environment, Water, Heritage and the Arts, 2008.

1.2.1 Energy consumption

Even though they represent only 2.8 percent of the Earth's land area[1] , cities are responsible for two thirds of the world's energy consumption[2](IEA, 2008). Some cities consume as much energy as entire countries: London for instance, with a population around 7.8 million, consumes about as much final energy as Ireland[3].

Energy use per inhabitant tends to be smaller in cities than in rural areas in developed countries. Indeed, higher density settlement in cities leads to energy efficiency gains, especially in transportation. For example, in the European union, in 2006, final energy demand on a per-capita basis was about 3.5 Million Tonnes of Oil Equivalent (Mtoe) in urban areas, slightly lower than the EU average of 3.7 Mtoe per capita, and than the average per-capita consumption in rural areas of around 4.9 Mtoe. In the USA, each urban resident consumes 11% less transport than the average US resident (IEA, 2008).

By contrast, in the developing world, residential per-capita energy use tends to be significantly higher in cities than in rural areas: city dwellers tend to have higher incomes and better access to energy services. This income effect generally outweighs

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[1]Several figures exist for urban settlements total surface. This figure refers to all urban settlements, including their green areas and empty spaces, as measured by (adjusted) night-time lights (UNFPA, 2007, chapter 4). A discussion about alternative figures is given in Angel et al., 2005.

[2]All the following figures are given from the perspective of the location of final energy consumption.

[3]Source: UK department of energy and climate change, and Eurostat.
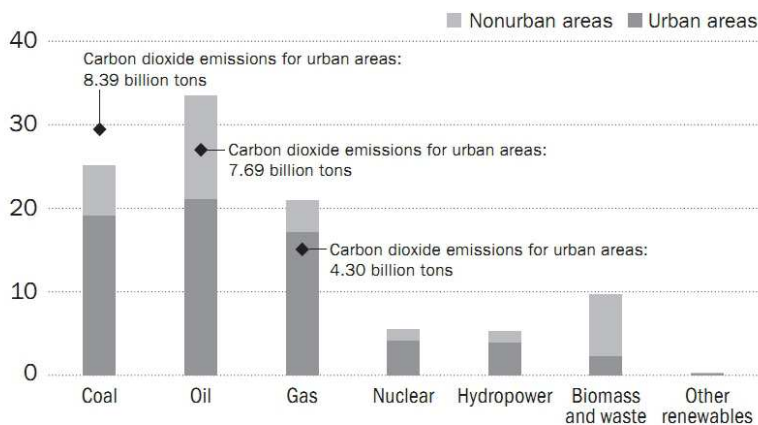
Figure 1.3: Energy demand as percent of total energy demand, and related carbon dioxide emissions 2005. Source: Hoornweg et al., 2011a.

the efficiency gains (IEA, 2008). An extreme example is given by china, where the per-capita energy use of urban areas is about 80% higher than in the country as a whole[4] (IEA, 2008).

Overall, the proportion of global energy consumed in cities is greater than the proportion of the world's population living in cities (66% compared to 50%).

1.2.2 GHG emissions

Cities probably emit between 30 and 40 per cent of all anthropogenic GHG emissions (Satterthwaite, 2008)(see Tab. 1.2). This share is lower than their share in energy consumption because of land-use and deforestation-related emissions which are generally not considered "urban".

When focusing on energy-related emissions, the pattern is different. The International Energy Agency (IEA), which devoted one chapter of it 2008 World Energy outlook (IEA, 2008) to energy use and GHG emissions in cities, estimated that energy use in cities translates into roughly 71% of global energy-related CO_2 emissions (an estimated 19.8 Gt of CO_2 in 2006, cf also Fig. 1.3)[5]. This figure is expected to rise to 74 percent by 2030, although the numbers vary widely depending on how cities or urban areas are defined (UN-Habitat, 2011). The share of global energy-related CO_2 emissions in cities is higher than that for energy use because as developing countries urbanize, they tend to shift from biomass and waste (assumed to be CO_2 neutral) to more CO_2-intensive energy sources (IEA, 2008)[6].

In developing countries city residents emit more CO_2 per capita because they tend to consume more energy than rural residents. This fact, coupled with the projected in-

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[4]On average, each urban citizen in China consumes 2.6 Mtoe, compared with 1.4 Mtoe nationally (IEA, 2008).

[5]This is more than four times the total emissions of China at that time.

[6]Adding non energy-related emissions, however, can lead to different conclusions. For instance, in Brazil, main sources of emissions at the national level are related primarily to rural activities, such as deforestation and cattle raising. If per capita energy-related CO_2 emissions are higher in Brazilian cities than in rural areas, total per capita CO_2 emissions follow a different pattern (Dodman, 2009).

Sector	Percentage of global GHG emissions	Justification for estimating the proportion of GHGs from cities, from the perspective of the location of activities that produced them	Percentage of GHGs allocated to cities
Energy supply[a]	25.9	A high proportion of fossil fuel power stations are not in cities, especially the largest cities. One third to one half of emissions from city-based power stations.	8.6-13.0
Industry	19.4	A large proportion of heavy industry (which accounts for most GHGs from industry) is not located in cities, including many cement factories, oil refineries, pulp and paper mills, metal smelters. Two-fifths to three-fifths of emissions in cities.	7.8-11.6
Forestry[b]	17.4	No emissions assigned to cities.	0
Agriculture	13.5	Some large cities have considerable agricultural output, but mostly because of extended boundaries encompassing rural areas. No emissions assigned to cities.	0
Transport	13.1	Private use of motor vehicles a large part of this. Should commuting by car by those living outside cities be assigned to cities? Should city dwellers driving outside city boundaries be assigned to their city? 60 to 70 per cent of emissions assigned to cities.	7.9-9.2
Residential and commercial buildings	7.9	Large sections of middle- and high-income groups in developed countries live outside cities - and a significant and increasing proportion of commercial buildings are located outside cities.60 to 70 per cent of emissions assigned to cities.	4.7-5.5
Waste and wastewater	2.8	More than half of this is landfill methane; but a proportion of this would be released outside urban boundaries from waste generated inside cities. 54 per cent of emissions assigned to cities.	1.5
Total[c]	100		30.5-40.8

[a] A large part of this is from fossil fuel power stations. Excludes refineries, coke ovens, etc., which are included under industry.

[b] Land use and land-use changes.

[c] Total emissions for the GHGs covered by the Kyoto Protocol amounts to 49 billion tonnes of CO2eq.

Table 1.2: Cities' contribution to global anthropogenic GHG emissions, by sector. Source : UN-Habitat, 2011, after IPCC, 2007c; Satterthwaite, 2008.

crease in global urbanization, produces an expected trend towards an increasing proportion of global CO_2 emissions from cities. The implementation of new climate-change policies in cities is therefore especially important (IEA, 2008).

1.2.3   An heterogeneous pattern

Emissions of cities vary widely across the world. The World Bank has listed urban greenhouse gas baselines for about 70 cities (Tab. 1.3, after Hoornweg et al., 2011a). While the methodology and data available for each city may vary, Tab. 1.3 is a useful starting point for first international comparisons. Some important trends emerge: developing countries tend to have lower per-capita emissions than developed countries; dense cities tend to have relatively lower per-capita emissions (particularly those with good transportation systems); cities tend to have higher emissions, if they are localized in a cold climate zone (Hoornweg et al., 2011a).

An important conclusion is that, even if rich cities tend use more energy than poor cities and therefore emit more greenhouse gas emissions, for similar climatic conditions there is no inevitable relationship between economic wealth and increasing emissions. This is especially true when greenhouse gas accounting excludes the consumption of manufactured goods within cities: per capita emissions can be comparatively low in cities that are efficient and well planned. For example, Tokyo and Seoul are much richer than Beijing and Shanghai, but emissions per capita are twice to three times smaller[7] (Hoornweg et al., 2011a). To understand which characteristics or policies enable to follow a low-carbon pathway, we have to examine more precisely the different sources of emissions and energy consumption in cities; this is the subject of the next section.

1.3   A local perspective on GHG emissions: sectoral analysis[8]

GHG are emitted in cities by various sectors and activities. This section briefly explores the main sources of emissions and the potential of mitigation. Many excellent reviews of of urban emissions exist (Dodman, 2009; Rosenzweig et al., 2011; UN-Habitat, 2011; Hoornweg et al., 2011a to cite the most recent ones), so this section will only present some key elements and conclusions that emerge from this literature.

1.3.1   Different sectors

Globally, different activities or sectors emit different quantities of different gases, with diverse impacts upon climate change (for instance, see Fig. 1.4): consumption of fossil fuels for energy production, industrial processes, waste decomposition, agriculture and land-use change. The main sources of GHG emissions from urban areas (Tab. 1.2) are related to energy production, even if waste emissions do play an important role

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[7]In 2005, GDP per capita in Seoul (23,000 $) and Tokyo (36,000 $) were two and three times higher than in shanghai (11,000 $) and Beijing (9,000 $). Emissions per capita were 4.1tCO_2e in Seoul, 4.9tCO_2e in Tokyo, 11.7tCO_2e in Shanghai and 10.1tCO_2e in Beijing (Hoornweg et al., 2011a). See alsoDhakal (2004) for an in-depth analysis.

[8]This whole section draws extensively on Dodman, 2009 and UN-Habitat, 2011

Country	Annual GHG emissions (tCO2e/capita)	and year	City	Annual GHG emissions (tCO2e/capita)	and year	Country	Annual GHG emissions (tCO2e/capita)	and year	City	Annual GHG emissions (tCO2e/capita)	and year
Argentina	7.64	2000	Buenos Aires	3.83		Portugal	7.71	2007	Porto	7.3	2005
Australia	25.75	2007	Sydney	0.88	2006	Republic of Korea	11.46	2001	Seoul	4.1	2006
Bangladesh	0.37	1994	Dhaka	0.63		Singapore	7.86	1994			
Belgium	12.36	2007	Brussels	7.5	2005	Slovenia	10.27	2007	Ljubljana	9.5	2005
Brazil	4.16	1994	Rio de Janeiro	2.1	1998	South Africa	9.92	1994	Cape Town	11.6	2005
			Sao Paulo	1.4	2000	Spain	9.86	2007	Barcelona	4.2	2006
Canada	22.65	2007	Calgary	17.7	2003				Madrid	6.9	2005
			Toronto (City of Toronto)	9.5	2004	Sri Lanka	1.61	1995	Colombo	1.54	
			Toronto (Metropolitan Area)	11.6	2005				Kurunegala	9.63	
			Vancouver	4.9	2006	Sweden	7.15	2007	Stockholm	3.6	2005
China	3.4	1994	Beijing	10.1	2006	Switzerland	6.79	2007	Geneva	7.8	2005
			Shanghai	11.7	2006	Thailand	3.76	1994	Bangkok	10.7	2005
			Tianjin	11.1	2006	UK	10.5	2007	London (City of London)	6.2	2006
			Chongqing	3.7	2006				London (Greater London Area)	9.6	2003
Czech Republic	14.59	2007	Prague	9.4	2005				Glasgow	8.8	2004
Finland	14.81	2007	Helsinki	7	2005	US	23.59	2007	Austin	15.57	2005
France	8.68	2007	Paris	5.2	2005				Baltimore	14.4	2007
Germany	11.62	2007	Frankfurt	13.7	2005				Boston	13.3	
			Hamburg	9.7	2005				Chicago	12	2000
			Stuttgart	16	2005				Dallas	15.2	
Greece	11.78	2007	Athens	10.4	2005				Denver	21.5	2005
India	1.33	1994	Ahmedabad	1.2					Houston	14.1	
			Delhi	1.5	2000				Philadelphia	11.1	
			Kolkata	1.1	2000				Juneau	14.37	2007
Italy	9.31	2007	Bologna	11.1	2005				Los Angeles	13	2000
			Naples (Province)	4	2005				Menlo Park	16.37	2005
			Turin	9.7	2005				Miami	11.9	
			Veneto (Province)	10	2005				Minneapolis	18.34	2005
Japan	10.76	2007	Tokyo	4.89	2006				New York City	10.5	2005
Jordan	4.04	2000	Amman	3.25	2008				Portland, OR	12.41	2005
Mexico	5.53	2002	Mexico City (City)	4.25	2007				San Diego	11.4	
			Mexico City (Metropolitan Area)	2.84	2007				San Francisco	10.1	
Nepal	1.48	1994	Kathmandu	0.12					Seattle	13.68	2005
The Netherlands	12.67	2007	Rotterdam	29.8	2005				Washington, DC	19.7	2005
Norway	11.69	2007	Oslo	3.5	2005						

Table 1.3: Representative GHG baselines for selected cities and countries. Source: World Bank, Hoornweg et al., 2011a.
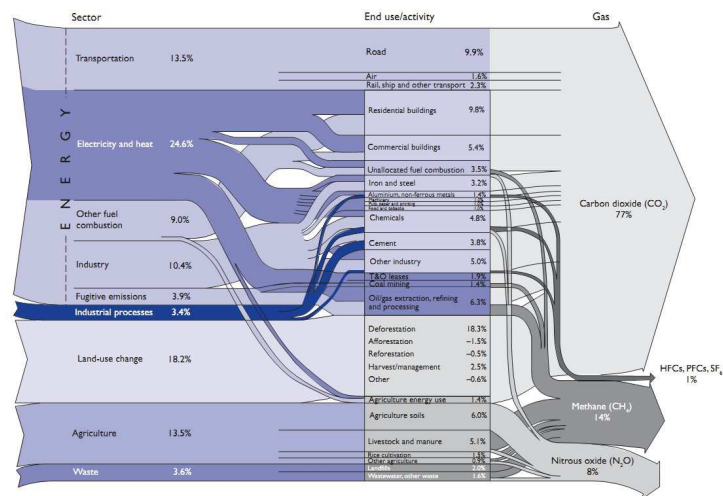
Figure 1.4: Global GHG emissions by sector and end use/activity. All data is for 2000. All calculations are based on CO_2 equivalents, using 100-year global warming potentials from the IPCC (1996), based on a total global estimate of 41,755 MtCO$_2$ equivalent. Land use change includes both emissions and absorptions. Dotted lines represent flows of less than 0.1% percent of total GHG emissions. Source: World Resources Institute.

in cities in developing countries. Following discussions will focus on energy-related GHG emissions: manufacturing, transport, services and residential buildings.[9]

Manufacturing on one side, and buildings, services and transport on the other side follow different dynamics. Whereas manufacturing emissions have decreased in some OECD countries where mitigation policies have been implemented, buildings, services and transportation energy consumption (Fig. 1.5(a)) and emissions (Fig. 1.5(b)) have increased over time. Fig. 1.6 presents equivalent results for France.

Part of the explanation comes from the fact that whereas manufacturing emissions are mainly driven by cost maximizing behaviors, and can react well to financial incentives such as energy prices increase, other sectors appear to be mainly driven by non-monetary preferences, and do not respond as well to price incentives. Some studies even measured negative GHG emissions abatement costs in these sectors, through the implementation of efficiency measures (Fig. 1.7). Let us examine now these sectors in more detail.

1.3.2 Commercial and residential buildings

GHG emissions from commercial and residential buildings are associated with both direct emissions (onsite combustion of fuels), indirect emissions (from public electricity use for street lighting and other activities and district heat consumption) and emissions associated with embodied energy (e.g. in the materials used for their construction) (UN-Habitat, 2011). They seem to account for a significant share of urban GHG emissions, even if due to the non-comparability of urban emissions inventory, it is not possi-

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[9]See for instance UN-Habitat (2011) for a detailed discussion on waste emissions. An important idea concerning this sector is that emission level are greatly determined by the development level. Urban areas have the potential to greatly reduce — or even eliminate — emissions from waste, because the concentration of people and activities in urban areas means that waste can be collected efficiently, and methane emissions from landfills can be captured and flared or used to generate electricity.
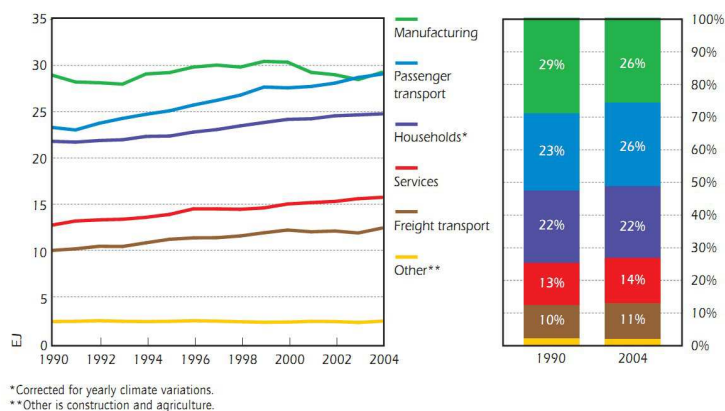
(a) Total final energy consumption by Sector, IEA14.
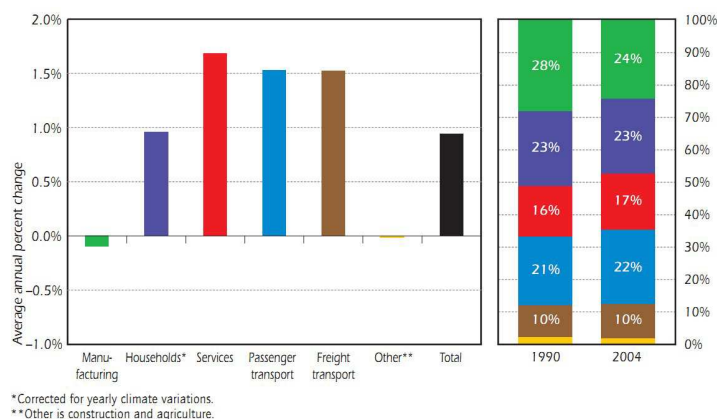
(b) Changes in CO_2 emissions, and emission shares by sector, IEA14.

Figure 1.5: Final energy consumption and emissions by sector, IEA14. Source: IEA, 2007.
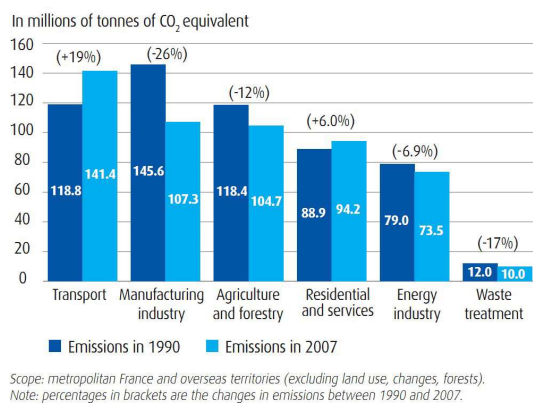
Figure 1.6: Changes in GHG emissions per sector in France between 1990 and 2007. Source: SOES, 2010, after Citepa, UNFCCC, December 2008.
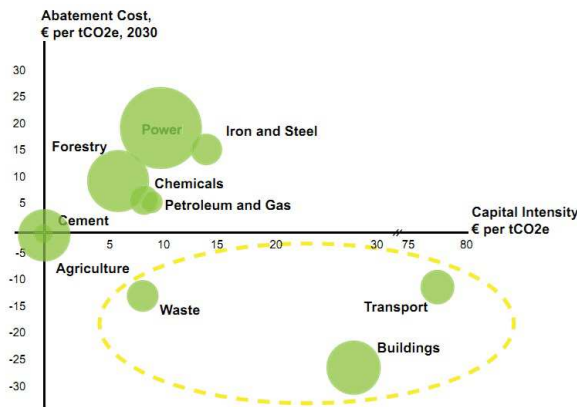
Figure 1.7: The "low hanging fruits" of urban GHG mitigation. Source: ICLEI, 2010, after McKinsey & Company, 2009.

ble to exact global figures. For instance, according to Tab. 1.2, they represent between 15% and 40% of global cities emissions, whether energy supply-related emissions are fully associated to these emissions or not. To take another example, in Paris, they represent 27% of total GHG emissions (based on the "bilan carbone" method, source: City of Paris and ADEME).

Residential buildings   As shown in Fig. 1.8, in IEA 15 countries, overall residential emissions[10] have increased over the period from 1990 to 2004, mainly driven by electricity use for appliances.

This graphic shows also the repartition of emissions by end-use: space heating is the main contributor, but appliances are rapidly approaching the same level[11]. The type of fuel used for electricity production, heating and cooling is a main determinant of this repartition, and of GHGs emitted. For instance, in France, emissions due to appliances are negligible compared to heating-related emissions, because of the low carbon content of electricity production (SOES, 2010). Prague uses less energy per capita for heating than New York City, but its emissions from heating are higher due to its reliance on coal. The emissions of Cape Town and Geneva are also higher than other comparable cities due to the predominance of oil instead of natural gas for heating (UN-Habitat, 2011).

Another important factor is average dwelling size: larger houses consume more energy for heating and cooling. Difference between countries and across time can be big. For instance, the average size of homes built in the United States has increased significantly, from 139m² in 1970 to 214m² in 2005. It is much greater than average dwelling size in the UK (87 m²) (Gupta and Chandiwala, 2009). This can be illustrated by Fig. 1.9, which shows a decomposition of changes in residential CO_2 emissions, for IEA 15 countries. "Activity" (i.e. population variation) and "structure" effects (i.e i.e. higher levels of appliance ownership and use and increased dwelling size area per

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[10]Excluding embodied energy, and corrected for yearly climatic variations.

[11]The energy and CO_2 emissions increases from appliances are now being driven by a wide range of mostly small appliances, as well as by air conditioning in some countries. Policies such as minimum energy performance standards have had some impact in curbing the increase in energy consumption of large appliances. However, these large appliances now represent only 50% of total appliance energy consumption, and this share is falling (IEA, 2007).
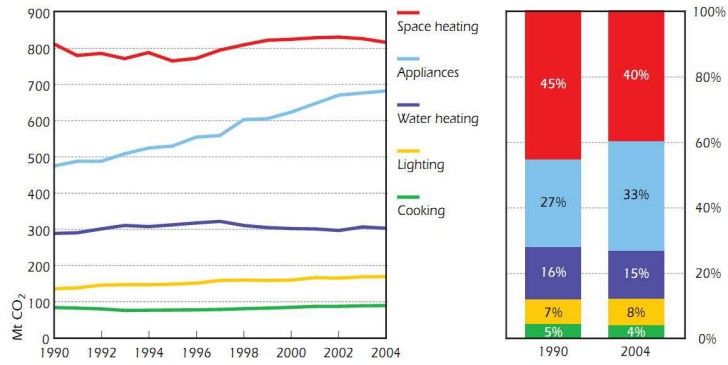
Figure 1.8: Household CO$_2$ Emissions by End-use, IEA15. Source: IEA, 2007
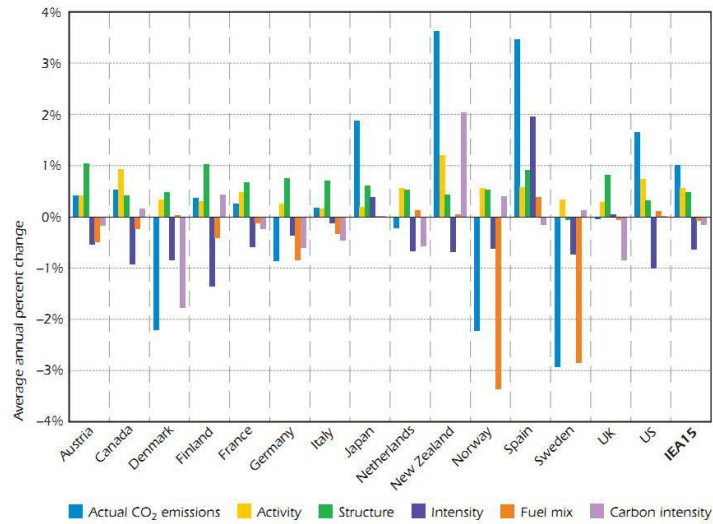
Figure 1.9: Decomposition of Changes in Household CO$_2$ Emissions, 1990 - 2004. Source: IEA, 2007. "Activity" represents population variation, "structure" appliance ownership and dwelling size area per person and "intensity" energy used per floor area or per appliance.
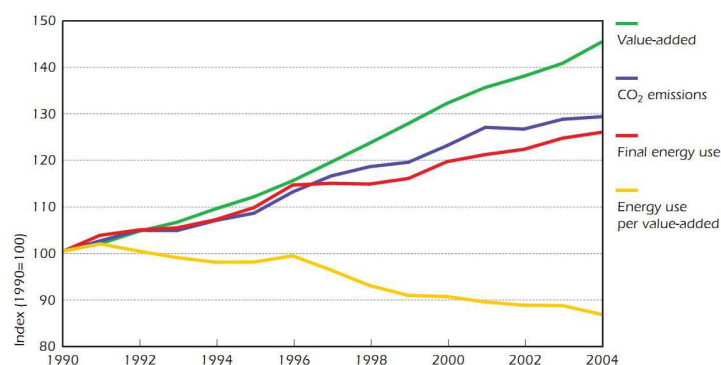
Figure 1.10: Overview of Key Trends in the Service Sector, IEA19. Source: IEA, 2007

person), are the main cause of residential CO_2 emissions variation.

Services and commercial buildings   Between 1990 and 2004, CO_2 emissions from services and commercial buildings rose by 29% (Fig. 1.10), with an especially important increase in electricity consumption, which reflects the growing importance of electricity-using devices such as lighting, office equipment and air conditioning. Even if in some countries, a decrease in energy intensity (energy consumed per output unit) has been observed,[12] energy consumption has been driven by rising output from the sector (as measured by value-added), which increased by 45%. (IEA, 2007).

Contrary to residential buildings, few disaggregated end-use data about services are available, but it seems that thermal uses of energy (space heating, water heating and cooking) account for just over half of the total energy use in services. Space cooling still has a relatively small share, but is growing rapidly in many countries (IEA, 2007). Table 1.4 presents for instance data for Canada and the United Kingdom.

| | Space heating | | Space cooling | | Lighting | | Other | | Total | |
	Electricity	Other fuels	Electricity	Other fuels	Electricity	Other fuels	Electricity	Other fuels	Electricity	Other fuels
Canada	4	36	7	0	13	0	29	11	53	47
United Kingdom	7	39	5	0	20	0	17	12	49	51

Table 1.4: Percentage Share of Service Sector Energy Consumption by Energy Commodity and End-use, 2004. Source: IEA, 2007.

1.3.3 Transports

Urban areas rely heavily on transportation for both internal and external movements of goods and people. Globally, transportation is responsible for about 23 per cent of total energy-related GHG emissions and 13 per cent of global GHG emissions (IPCC, 2007c). Similarly to buildings-related emissions, freight and passenger transport emissions have increased over recent years, both in developed countries and in developing

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[12]Between 1990 and 2004 there was an overall decline of 14% in the energy intensity of the service sector (as measured by final energy use per unit of value-added).
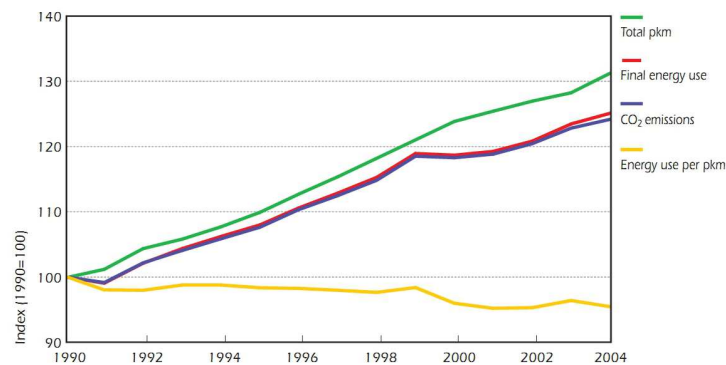
Figure 1.11: Overview of Key Trends in Passenger Transport, IEA17. Source: (IEA, 2007).

countries. IEA has for instance measured that between 1990 and 2004, CO_2 emissions of passenger transport (both urban, rural and inter-urban) rose by 24%, mainly driven by the 31% increase in passenger travel (measured by the number of passenger-kilometres) (Fig. 1.10).

It is here again impossible to give exact global figures of urban transport emissions: according to Tab. 1.2, they represent between 25% and 30% of global cities emissions, and in Paris they represent 54% of total GHG emissions (based on the "bilan carbone" method, source: City of Paris and ADEME).

Little data exist specifically about urban transport, but both in developed and developing countries, urban transport activities, and transport emissions, appear to increase as economies grow. An illustrative example is China, where Darido et al. (2009) reports the CO_2 emissions from transport in 17 sample cities. On average, these emissions increased between 2002 and 2006 by 6 per cent per year, a figure which ranged from 2 to 22 per cent between the sample cities. The CO_2 emissions per capita from transport also increased in all cities and ranged between 0.5 and 1.4 tonnes per person in 2006, with Beijing being the highest.

A major determinant of passenger transport-related GHG emissions is transport mode. Indeed, emissions per passenger.km are extremely different depending on the mode. In cities, public-transport emissions per passenger km are generally between 100 and 20 times lower than cars emissions, and urban transport emissions depend mainly on the proportion of journeys made by private as opposed to public transportation. For instance, if in London, New York and Washington, DC, transportation represents a significant contribution to the cities' emissions (22, 23 and 18 per cent, respectively), figures are significantly lower than in in Barcelona (35 per cent), Toronto (36 per cent), Rio de Janeiro (30 per cent) and São Paulo (60 per cent), which are strongly reliant on private motor vehicle transportation(UN-Habitat, 2011, after Newman, 2006 and Dodman, 2009).

Transport emissions is an especially important issue in developing countries, where motor vehicle ownership is expanding rapidly. Worldwide, there are in 2011 about 1.2 billion passenger vehicles. This figure is projected to reach 2.6 billion by 2050, the majority of which will be found in developing countries (UN-Habitat, 2011,Wright and Fulton, 2005).

Several mitigation options exist, generally relying on advances in transport technology or on changes from one mode of transportation to another. As will be explained in

Section 2.4.2, when urban shape is appropriate —generally when densities of people, economic activities and cultural attractions are high enough— public transport system development can be effective. This is true in both developed and developing countries, as highlighted by Bogotá (Colombia), where a bus rapid transit system (known as TransMilenio) combined with car-restriction measures[13] has shown that an erosion of the relative importance of the public transport mode can be stopped (Lefèvre, 2007; Wright and Fulton, 2005). Similar systems have also been proposed for several cities in Africa — for example, in Dar es Salaam (UN-Habitat, 2011) — and in Asia (see for instance Lefèvre, 2009 for an analysis in Bangalore, India). Policies influencing urban transport emissions have generally many co-benefits: heavy reliance on personal transportation often results in urban air pollution, environmental degradation, as well as road traffic accidents (UN-Habitat, 2011).

One main issue — also discussed in more details in Chapter 3— is whether or not the urban shape is appropriate for public transport development and use, and whether urban policies should support an evolution towards such a shape — such policies are often expensive either financially or politically, as will be illustrated in Chapter 9— or rely on transport technology improvements. We will see in Chapter 8 that, in the case of a city such as Paris urban area, transport technology changes appear to have a much greater impact that planning policies aiming at orienting city shape evolution on a new pathway. As will be explained, the conclusion might be different for rapidly growing developing country cities.

1.4 Mitigation at city scale

1.4.1 The key role of urban planning

1.4.1.1 Urban shape and GHG emissions

The uses of land and spatial distribution of population and activities within an urban area (i.e. the "urban structure", or "urban form") plays a major role in determining its levels of energy use and GHG emissions. It is indeed one of the main determinant of the type of habitat, of networks efficiency, and of transport distances and transportation mode (e.g. the relative importance of public versus private modes).

The high concentrations of people and economic activities in urban areas can lead to economies of scale, proximity and agglomeration — all of which can have a positive impact upon energy use and associated emissions, while the proximity of homes and businesses can encourage walking, cycling and the use of mass transport in place of private motor vehicles (Satterthwaite, 1999). Dense urban settlements can be seen to enable lifestyles that reduce per capita GHG emissions through the concentration of services that reduces the need to travel large distances, the better provision of public transportation networks, and the constraints on the size of residential dwellings imposed by the scarcity and high cost of land (UN-Habitat, 2011).

The type of urban structure often defines the most efficient mode of transport. It has a direct impact on trip length, on the feasibility of transit or private cars being the dominant mode of transport. The famous comparison, made by Bertaud (2002), of Atlanta and Barcelona is illustrative of these points: in 1990, both cities had roughly

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[13]including 'car-free' Sundays in which 120km of arterial roadways are closed to private motorized vehicles (UN-Habitat, 2011)
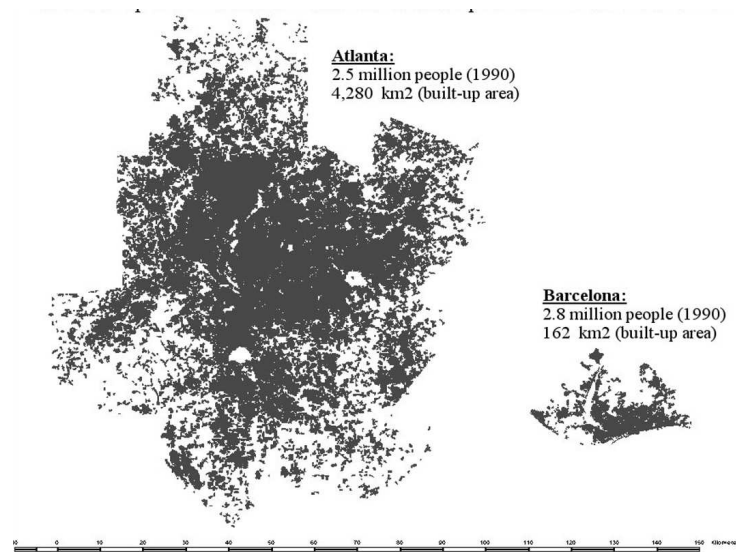
Figure 1.12: The Built-up Area and Barcelona represented at the same scale. Source: Bertaud, 2002.

the same population (2,5 million inhabitants) but very different average density (cf. Fig. 1.12).

Firstly, for a given population, built-up area will be smaller and trips will be shorter in length in cities with high densities than in cities with low density, potentially leading to an overall smaller transport demand. Smaller trips can also enable to a significant number of trips done by foot or bicycle. These two effects can be measured in Atlanta and Barcelona: whereas in Atlanta the longest possible distance between 2 points within the built-up area is 137 km, in Barcelona it is only 37 km. At the time of the study, 20% of trips within Barcelona municipality were made by walking, whereas there share was negligible in Atlanta (Bertaud, 2002).

Secondly, higher population density enable to build efficient public transport networks. Barcelona's metro network is 99 kilometers long and, at the time of the study, 60% of the population was living at less than 600 meters from a metro station, whereas in Atlanta, only 4% of the population was living within 800 meters from a metro station of its 74km long network. To provide Atlanta's population with the same metro accessibility as Barcelona does (60% of the population within 600 meter from a metro station), Bertaud (2002) computed that additional 3,400 kilometers of metro tracks and about 2,800 new metro stations would be required, which is unrealistic. Comparison between bus lines length and number of bus stops in Barcelona and Atlanta would have given the same results.

Numerous other examples exist. A study of London shows for instance a "*positive link between higher density areas and levels of public transport access across London, which is reflected in the decisions that people make about how to get to work*" (Burdett et al., 2005). In France, a 2005 survey of means of transport used by people to reach their place of work or study shows that car use in urban centers is smaller than in peri-urban municipalities, and measures an opposite effect for public transport use (Fig. 1.13(a)). Different availabilities of public transport appears to be a major cause of this result (Fig. 1.13(b)).

It has been measured that an average household in 48 major US metropolitan ar-
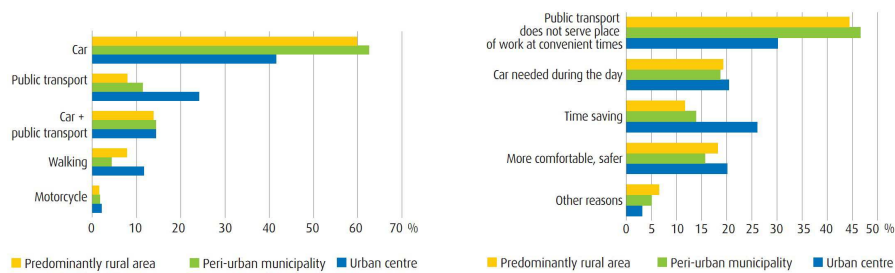
(a) Means of transport used by people surveyed to reach their place of work or study.

(b) Reasons for using car.

Figure 1.13: Modal choice for commuting trips in France. Source: SOES (2010), after Insee, "Pratiques environnementales des ménages" (ongoing survey on households environmental habits), January 2005 (table taken from Insee, 2007).

eas generates up to 35 percent less greenhouse gas emissions when located in the city than when located in the corresponding suburb[14] (Glaeser, 2009). The city of Toronto, for which some of the most comprehensive spatial data are available (Hoornweg et al., 2011a), provides an important observation on spatial distribution of greenhouse gas emissions: detailed neighborhood greenhouse gas emissions inventories showed a variation from a low of 1.31 tCO_2e per capita in an area with multifamily units proximate to services and public transit, to a high of 13.3 tCO_2e per capita in a typical sprawling neighborhood with large single family homes distant from all services and totally automobile dependent (VandeWeghe and Kennedy, 2007). As the distance from the central core increases, private motor vehicle emissions begin to dominate the total emissions.

This pattern is supported by an earlier study, which found that low-density suburban development in Toronto is 2 to 2.5 times more energy and GHG intensive than high-density urban core development on a per capita basis (Norman et al., 2006). This suggests that "*what you buy is important, but where you live is much more important, especially if you take into account the weather conditions and the rigid patterns of emissions associated with urban form and buildings*" (Hoornweg et al., 2011a). Finally, we should cite the influential study by Newman and Kenworthy (1989) which was one of the firsts to suggest that gasoline use per capita declines with urban density, although the relationship measured weakens once GDP per capita is brought into consideration (UN-Habitat, 2011).

Density may also affect household residential energy consumption. More compact housing uses less energy for heating. For example, households in the US living in single-family detached housing consume 35 per cent more energy for heating and 21 per cent more for cooling than comparable households in other forms of housing (UN-Habitat, 2011). In addition, dense urban areas generate a more intense urban heat-island effect (cf. Box in Section 2.1.1): this increases the number of 'cooling days' and decreases the number of 'heating days', with the latter tending to have a greater effect on energy consumption. Consequently, residential buildings in dense urban areas tend to consume lower levels of energy (Ewing et al., 2008).

Naturally constrained cities, such as Singapore, Hing Kong, Portland, Seattle, Barcelona, and Vancouver, provide important lessons: Geography—oceans and mountains—limits

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[14]The largest difference is seen in New York City where a Manhattan household generates 6.4 tCO_2e less than their suburban neighbors.

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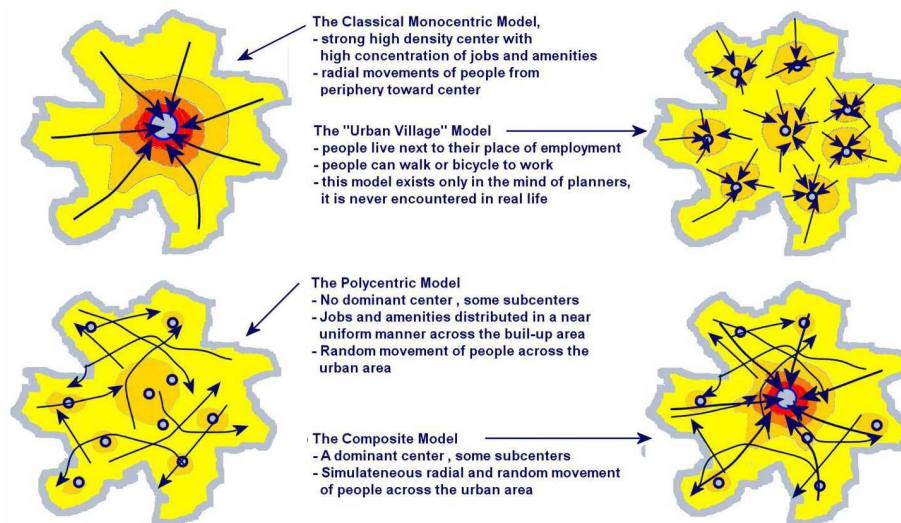
Figure 1.14: Defining spatial structure: the pattern of trips. Source: Alain Bertaud "Order without design" (to be published).

the land available for development in these cities and has forced them to develop up in a high density mode that has led to lower greenhouse gas emissions (Hoornweg et al., 2011a).

Energy production in low-density cities   It should be noted that, if less-density cities may be less adapted to reduced transport-related energy consumption than compact cities, low densities may be compatible with climate-friendly development. Indeed, it may enable larger decentralized renewable energy production in the city (e.g. photovoltaic panels on roofs), which may counterbalance transport-related increased energy need (Giraud et al., 2010). This scenario is dependent on future transport and renewable energy production technologies, but may potentially disentangle climate and density issues.

1.4.1.2   Beyond the density concept

The debate about sustainable urban shape has long turned around the issue of density. However, density is just one of a variety of factors that influences the sustainability of urban form (Neuman, 2005). For instance, Jabareen (2006) has identified seven concepts for a sustainable urban form — namely, compactness, sustainable transport, density, mixed land uses, diversity, passive solar design, and greening. Based on these criteria, the 'compact city' model is identified as being most sustainable, followed by the 'eco-city', 'neo-traditional development' and 'urban containment' — although this classification and ranking is based on reviews of literature rather than empirical research (UN-Habitat, 2011). Strategies to increase urban density may or may not have a positive influence on GHG emissions and other environmental impacts.

An interesting analysis is given by Bertaud (2002). He distinguishes four urban structures: In the first, "mono-centric", represented by such cities as New York (US), London (UK), Mumbai (India) and Singapore, most economic activities, jobs and amenities are concentrated in the central business district (CBD). Most commuters

travel from the suburbs to the CBD and public transport can be promoted. The second, "poly-centric", exemplified by such cities as Huston (US), Atlanta (US) and Rio de Janeiro (Brazil), jobs and amenities are distributed across the built-up area, and most trips are from suburb to suburb. A very large number of possible travel routes exists, but with few passengers per route, and public transport is difficult and expensive to operate. The third, "urban village" is an ideal city where people live close to their place on employment. It has often been the aim of urban planners, however it is not feasible, as "*it implies a systematic fragmentation of labour markets which would be economically unsustainable in the real world*". It would require firms not to take advantage of spillover economies (cf. following box), and people to restrict their job searches to businesses within walking or biking distances from their homes, or to always move in new homes close to their job[15]. The last city structure, "composite", is the most common type of urban spatial structure with a dominant center together with a large number of jobs located in the suburbs. Public transport can be promoted for trips from the suburbs to the CBD, trips from suburb to suburb are more easily made with public transport

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Spillover economies

What characterizes cities is a concentration of population and goods in a reduced space; in economics, it is assumed that cities exist mainly because they draw in businesses who wish to take advantage of spillover economies (cf. Duranton and Puga, 2004). This designates a growth in productivity caused by geographical proximity. It might for example mean the geographical proximity of businesses in the same sector, to have access to specialized products or experts that could not be found without this concentration (for example concentrations of banks in financial districts) or the geographical proximity of businesses in different sectors where the diversity of skills and experience encourages innovation. Empirical research confirms that spillover economies are substantial; average increases in productivity of between 4% and 20% have been measured across cities for each doubling of population. These effects are particularly noticeable in certain industries and especially in certain services (Rosenthal and Strange, 2004).

1.4.1.3 Acting on urban shape, in practice

If urban shape appears to be an important determinant of GHG emissions, it is a difficult lever to use, once city are already built: structural modifications in cities occur slowly over a long time horizon, and cities have a tendency to lock-in the form that they grow into. As will be studied in more details in Chapter 4, one of the major determinant of a city shape is its transport system: "*Once buildings grow around transportation and service nodes, they are all but locked-in*" (Hoornweg et al., 2011a). For instance, while many US cities are defined by their reliance on the automobile for most travels, European cities tend to be more compact, with a greater reliance on public transportation. It is therefore especially important to ensure that current rapidly growing developing world cities adopt urban shapes which will not constrain future mitigation strategies.

The comparison between Atlanta and Barcelona, from Bertaud (2002), is, again, a good illustration of this idea. At the time of the study, average density was 6 people per hectare in Atlanta, compared to Barcelona 171 p/ha. In Atlanta, reaching a 30 p/ha threshold (which roughly corresponds to the lowest threshold to enable efficient public transport) over a period of 20 years, assuming that the historical population growth rate

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[15]it is for instance impossible for couples who do not work in close locations.

of 2.7% per year continues uninterrupted, would require the current built-up area to shrink by 67 %. "*In other words, about 67% of the existing real estate stock would has to be destroyed, the land over which it lays has to revert to nature and its population and jobs have to be moved into the 33% of the city which would remain*" (Bertaud, 2002), which appears difficult to implement in practice.

1.4.2 Cities role in global mitigation policies

1.4.2.1 Cities can play a major role

Cities can play a major role in global efforts to reduce GHG emissions, for three reasons (UN-Habitat, 2011):

First, municipal governments often have jurisdictional responsibility for key processes — land-use planning, transportation, waste collection and disposal, and energy consumption and generation — which shape GHG emissions (UN-Habitat, 2011). They can also generate strong markets for efficient energy products and service: cities can promote green growth through their screening of investments in infrastructure and transport, financial and tax incentives, partnerships, regulation of energy suppliers, increased consumer awareness, and job training (Hoornweg et al., 2011a). As explained in Giraud et al. (2010), local authorities have two principal options in reducing GHG emissions. As an organizational entity, they have direct control on energy use in public buildings, public fleet, etc. The first option is therefore to target these emissions. The second option consists in using their capacities and policy levers to reduce GHG emissions from activities occurring within their administrative area on which they have direct or indirect influence: locally provided public services, land-use zoning, transportation, natural resources management, buildings, and waste and water services (Betsill, 2001; Bulkeley and Kern, 2006; Betsill and Bulkeley, 2007; Corfee-Morlot et al., 2009; Kamal-Chaoui and Robert, 2009). However, this tool is not always easy to use, because external factors, beyond urban decision-makers policies, may also have comparable influence on these areas, and because using this tool might have side-effects on other urban policy goals. This issue is studied in more details in Chapter 3, and we will see in Part III that it is possible to address it through the use of an integrated model (cf. Chapters 9 and 8).

Second, drivers of emissions — and mitigation options — differ across the world, and depend on geographic, climatic, economic and cultural conditions. Cities and metropolitan authorities are often well positioned to develop policy solutions adapted to their local context (Giraud et al., 2010). It is increasingly clear that non-governmental actors have a significant role in addressing climate change at the urban level. Private-sector organizations and civil society groups are now involved in a range of measures (e.g. promoting behavioral change and reducing energy use in commercial buildings) independently of local and national governments. Municipal governments often provide a key interface for engagement with stakeholders in the private sector and civil society (UN-Habitat, 2011). Furthermore, given their ability to influence many policies that address diffuse emissions sources, local authorities can implement both short- and long-term policies that influence emissions sectors—and often go beyond the direct influence of national governments (Giraud et al., 2010).

Third, the concentration of people/business in urban areas means that solutions (e.g. mass transit or requirements for energy savings in offices) are feasible. In other words, cities can act as laboratories where solutions for addressing climate change can be tried and tested (UN-Habitat, 2011). At city geographic scales, experimentation and

learning can be expected to be more rapid and lessons learnt can disseminate more quickly than at bigger scales, and lessons from such experience may filter up or over to influence action elsewhere (Corfee-Morlot et al., 2009).

1.4.2.2 Benefits of a multi-scale approach for coping with climate change

Involving cities as key actors in global GHG emissions reduction can be very efficient (Ostrom, 2009). Waiting for a single worldwide "solution" to emerge from global negotiations is indeed problematic, because each country has an incentive to wait for the others to act first. It is the free-rider problem. While GHG emissions reduction policies benefit to all countries as a whole, each state has privately an incentive to adopt as few mitigation policies as possible, as they can harm its economic competitiveness. In practice, considerable disagreements exist even among the major states, and there has been a "*decades-long failure at an international level to reach agreement on efficient, fair, and enforceable reductions of greenhouse gas emissions*" (Ostrom, 2009).

Efforts to reduce global GHG emissions can be best addressed at multiple scales and levels: contrary to states, cities have generally privately much to gain from embracing the low-carbon agenda, and are therefore not really threatened by free-riding issues. The cobenefits of green action often more than cover the costs. Increased efficiency can lead to cost savings and energy security, which can compensate for the initial investment[16]. Reducing pollution has a direct impact on health, quality of living, attraction of private capital and human resources. Finally "*embracing such an important global cause helps cities to position themselves within a group of leaders, access information and technology, and learn by doing.*" (Hoornweg et al., 2011a).

Even if, alone, cities efforts in mitigating global GHG emission may not be sufficient to reach ambitious global targets, there is therefore much to gain in supporting it. "*Given the slowness and conflict involved in achieving a global solution to climate change, recognizing the potential for building a more effective way of reducing green house gas emissions at multiple levels is an important step forward.*" (Ostrom, 2009). In Chapter 8, we will show an example of the link between global and local mitigation efforts.

1.4.2.3 Cities are actually taking action

Numerous cities are actually taking action on climate change, sometimes even without national pressure: Stockholm, Toronto, Copenhagen, New York, as well as smaller cities such as Mannheim (Germany), Nantes (France), Boulder (United States)... For instance, here is a brief summary of some urban climate change strategies (See for instance Rosenzweig et al. (2011); Hoornweg et al. (2011a); Rosenzweig et al. (2010) for other examples):

Paris (2,230,000 inhabitants, 105 km²)   In October 2007, Paris adopted a climate strategy ("plan climat") involving a wide range of measures on transport, urban planning, waste, residential sector etc. The aim is to decrease, in 2020, the city's GHG emissions by 25%, compared to 2004. Objective for the city's administration emissions are stricter: 30% in 2020, with a 30% decrease of city's administration buildings and public lighting energy consumption and 30% of the energy provided by renewable

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[16]for instance, investment costs were recovered by savings in energy bills after three years, when the city of Los Angeles retrofitted most of its public buildings. (Hoornweg et al., 2011a).

resources. Policies encompass a renovation of Paris schools, financial help to landowners to better insulate their buildings, an optimization of public vehicle use and of public lighting, the installation of a total of 200 000m² of photovoltaic panels, and financial help and stricter insulation norms for new social housing buildings.

Greater Lyon (1,300,000 inhabitants, 500 km²)   The climate strategy was adopted in November 2007, with an aim to decrease the city's GHG emissions by 20% in 2020 compared to 2004. Policies encompass financial help and stricter insulation norms for new social housing buildings, the development of a more integrated public transport network and installation of photovoltaic panels.

Greater London (7,800,000 inhabitants, 5000 km²)   In its climate strategy, the Greater London aims at achieving a 60% reduction in London's emissions by 2025, by ensuring that "25% of London's energy is delivered through more efficient decentralized energy", by "improving the energy efficiency of London's homes and buildings" and by reducing emissions from transport. (Source: Greater London Authority). Measured encompass for example the "RE:NEW" policy, giving households energy efficiency advice and installing for free simple energy efficiency improvements[17], the development of area wide district heating networks, encouraging clean transport technologies such as hybrid buses or cycling throughout the city.

Several international city alliances have also been created to disseminate information. For instance, ICLEI ("local governments for sustainability") is an international association of local governments that have made a commitment to sustainable development. The World Mayors Council on Climate Change was founded by Kyoto's mayor in December 2005, following the entry into force of the Kyoto Protocol. The C40 Cities Climate Leadership Group of large cities, launched in October 2005, now has 40 participating and 19 affiliate cities.

1.5   Conclusion: GHG emission reduction in practice

This chapter has two main conclusions. First, cities can play a major role in global GHG emission reductions, because a significant share of global GHG emissions is under direct or indirect influence of urban governments, and because they often have more incentive to act than national governments as climate policies may be cheap or even profitable.

Several policies can be used, which require different anticipation levels. Whereas city's administration vehicles route optimization can be quickly implemented, the development of new public transport routes or renovation of a large number of buildings takes more time, and change in a city structure is even longer.

However, there is still a large uncertainties about how to design best climate strategies. First, there are large knowledge gaps in our understanding of optimal design of long-term policies, especially urban planning, because it is difficult to conduct experiments and because there is no fully comparable historical example. Side-effects and actual cost of such structural policies are also uncertain.

Second, the actual global effectiveness of short-term policies is also under debate. It remains unclear whether short-term policies such as energy efficiency measures in

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[17] such as "energy display devices, radiator panels, aerated taps and showerheads, hot water tank jackets and draught-proofing". Source: Greater London Authority

transport systems or energy and heat networks and infrastructures will be the cheapest, or the best option, or even simply sufficient, and to what extent they should be complemented by structural, long-term policies (cf. Allaire and Criqui, 2007). This issue is related to some extent to the uncertainty concerning global future evolutions, such as energy prices, or socio-economic changes, on which urban government have little or no influence.

These issues will be studied in more details in Chapter 3. Our thesis in the present work, is that they can be addressed, and that one tool to help doing so is integrated city modelling. Using such a model, we will deal with relative strength of short-term and long-term policies in Chapter 7 and 8, and with side-effects of structural policies in Chapter 9.

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Chapter 2

Cities and climate change vulnerability

This chapter is based on a report, written with Stéphane Hallegatte for ONERC[1] (Viguié and Hallegatte, 2010). It looks at the various impacts (positive and negative) that climate change may have on towns and cities, and on main reasons why cities are vulnerable to these impacts. It focuses on mainland French cities case.

This chapter will briefly look at the different impacts that climate change may have on urban environments. These impacts are very dependent on context, in particular the geographic zone and the way the city and the society under consideration function. Although we will briefly describe impacts that may affect cities in other parts of the world, we will focus here on French cities.

Few climate change impacts are specifically urban and most are also felt in rural areas. However some impacts will be particularly felt in urban areas. It is the case for heat waves, for instance, because of the heat island effect(cf Section 2.1.1). Some impacts will be identical in rural or urban areas but will call for particular responses in cities. For example natural hazards management cannot be undertaken similarly in areas with high or low population densities. The most distinctive specificity of climate change impacts in urban areas is their interdependence. Because cities are deeply integrated systems, and highly dependent on networks (water, electricity, transport, communications), impact on various sectors can interact, and should therefore be considered as a whole. A sector by sector approach appears particularly unsuited to large urban urban areas.

Most of following figures and data are taken from the work of the IPCC (IPCC, 2007a) and from ONERC reports (ONERC, 2009a and ONERC, 2009b). Knowledge concerning future climate change impacts is limited and unanticipated impacts may appear during the course of the century. It is equally possible that impacts may be less serious than we presently think.

Definition of vulnerability   An important idea is the difference between hazards, that may occur as a result of climate change, and vulnerability. Climate change may give

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[1] French National Observatory for Climate Change Effects
`http://www.developpement-durable.gouv.fr/-Impacts-et-adaptation-ONERC-.html`

Figure 2.1: Hazard, exposure, vulnerability and risk.

rise to changes in natural rhythms, i.e. events that may have a negative impact on society (*hazards*). These hazards will have a certain *probability*, which will change depending on the event under consideration. The *exposure* includes everybody and everything that might be affected by the event. For example this might mean all the population, buildings and facilities situated in a flood-prone area. Faced with events, a given city may be more or less negatively affected, depending on the way it has been planned, its history, its economy and its ability to adapt. *Vulnerability*[2] is measured by this degree to which a city may be negatively affected by the event (it depends on the existence of defense systems, the ease with which an affected area can recover etc.) Finally *risk* is the result from the three following components: the *hazard*, the *exposure*, and the *vulnerability* in the face of the event.

Reducing the risk requires action in each of these components. Here, mitigating an hazard or its probability is directly linked to mitigating climate change, i.e. reducing GHG emissions. Due to strong climate inertia and current trends in GHG emissions, it is certain that the climate will undergo large-scale changes during the 21st century and that we will therefore have to mitigate exposure and vulnerability to reduce the risk. Acting on these two factors is what is generally known as "adaptation" to climate change.

2.1 Risks to health

Climate change will lead to some health benefits, such a drop in mortality due to the cold, as winter temperatures rise. However, it is suggested that without suitable adaptive measures, health risks will increase, because of a recrudescence of heat waves (for instance in southern, central and eastern Europe) and a greater incidence of illnesses transmitted via food and vectors (mosquitos, ticks etc.).

2.1.1 Heat stress

The 2003 heat-wave (Fig. 2.2) caused an increase in mortality of 14,800 persons in France between August 1st and 20th. Victims were mainly older people: persons aged 75 and more represent 82% of deaths attributable to the heat wave. This heat wave cannot be directly attributable to climate change, as it could have taken place in a climate not modified by human activities. Nevertheless, figure 2.2 (b) shows just how exceptional it would have been in a non-modified climate. Climate change made this

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[2]In the literature, a debate exist on the exact definition of these concepts (cf. for instance Füssel, 2007). In the climate change community, for instance, "vulnerability" is often used as an equivalent of "risk", whereas "sensitivity" is used as an equivalent of our present definition of "vulnerability" (cf. glossary in IPCC, 2007a).
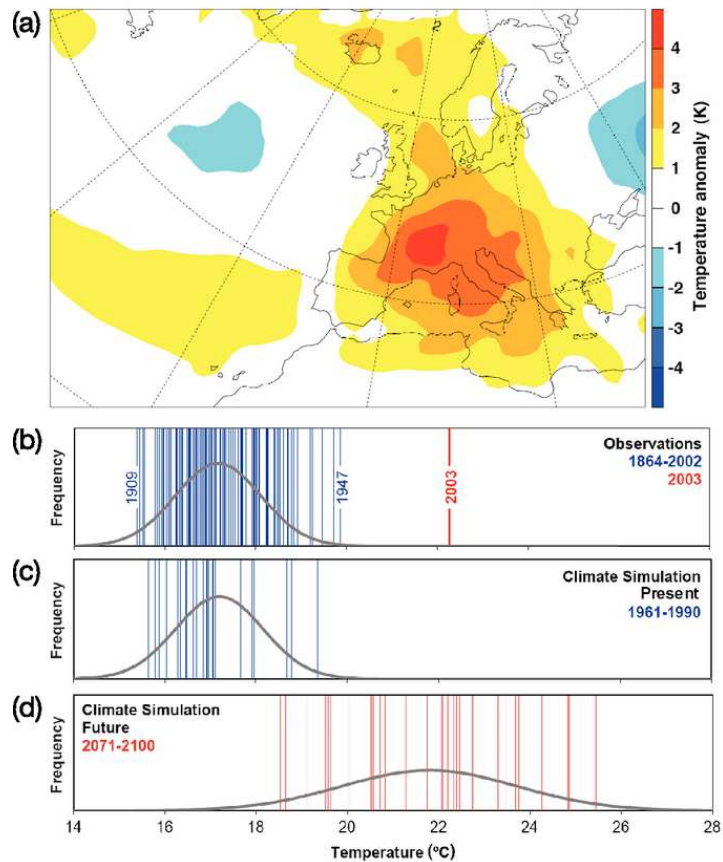
Figure 2.2: Characteristics of the summer 2003 heatwave (IPCC, 2007a after Schär et al., 2004). (a) JJA temperature anomaly with respect to 1961 to 1990. (b) to (d): JJA temperatures for Switzerland observed during 1864 to 2003 (b), simulated using a regional climate model for the period 1961 to 1990 (c) and simulated for 2071 to 2100 under the A2 scenario using boundary data from the HadAM3H GCM (d). In panels (b) to (d): the black line shows the theoretical frequency distribution of mean summer temperature for the time-period considered, and the vertical blue and red bars show the mean summer temperature for individual years.

event more likely and will have a tendency increase the probability of similar events more in the future, until it becomes a recurrent feature. Fig. 2.2(d) illustrates what could be a normal summer weather by the end of the century, according to some climate scenarios (if there is no global policy on the reduction of GHG emissions).

In all emission scenarios, climate model simulations show an increase in average summer temperatures and in temperature variability from one year to another. Taken together, these lead to an increased risk of summer heat-waves. Cities are particularly vulnerable to this impact because of the urban heat islands effect (cf. box). In several developed countries, the aging of the population reinforces the vulnerability to this impact, and increases health risks.
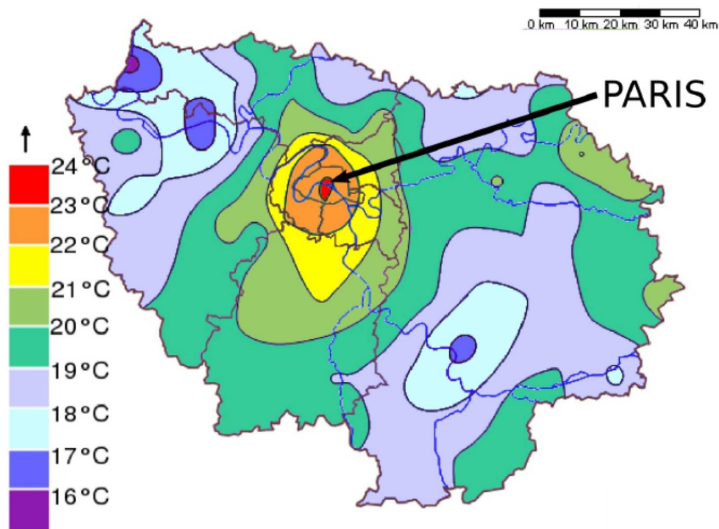
Figure 2.3: Minimum temperatures (night) in Paris and around Paris during the heat wave of 2003. We can see differences of up to 7°C created by the urban heat island effect. Source: V. Masson, G. Pigeon, A. Lemonsu, C. Marchadier, CNRM, Météo-France.

The Urban Heat Island effect

In towns and cities exist a micro-climate, due especially to the existence of urban heat island (UHI). This designates higher air temperatures, regularly observed close to the ground in urban areas, when compared to the rural areas that surround them. According to several studies looked at by Oke (1987), the maximum intensity of a UHI can go from 2°C for a town of 1000 inhabitants up to 12°C for a city of several million inhabitants.

For example, during the 2003 heat wave, the temperature differences were of 7°C between the centre of Paris and certain rural areas (Figure 2.3) In practice, the difference in temperature between the centre of a city and rural areas depends on the architectural characteristics of the city (such as its spread, its density and the height of the buildings) and the characteristics of the rural area used as a control.

A UHI has a recurrent daily variability and its intensity is generally stronger at night. It intensifies or forms progressively during the night time cooling period because of a rate of cooling that is slower in the more built up areas than in the periphery. In the majority of cases, the maximum attained by a UHI seems to be a few hours after the sun has set. Often the UHI diminishes rapidly after sunrise.

The intensity of the UHI diminishes as the wind rises. UHI disappears when wind speeds are over 11 m/s. When there is a moderate wind (3-6 m/s), the temperature field is shaped like an extended plume depending on the wind direction. In case of weak wind (< 2 m/s), THe UHI can be composed of several cells, and its shape varies according to land-use and urban heterogeneity.

The intensity of a UHI diminishes as cloud cover increases. Clouds act by modifying the night-time radiative cooling during which a UHI is formed. The influence of seasons was studied on cities in temperate climates and in other types of climates (Mexico and Cairo for example). It has been shown in these studies that UHIs are more frequent in summer and that they are weaker and less frequent when there is rain. Nevertheless, the maximum intensity of UHIs (the difference between temperatures in town and the rural areas that surround them) is the same whatever the season.

The impact on health will depend on the infrastructure in place, planning policies, types of homes and lifestyles. For instance, high temperatures and humidity in Paris during 2003 heat wave were close to those normally observed in Seville during an ordinary summer, but in Seville, these climatic conditions do generally not have such serious consequences. This is due to several reasons, but especially a built environment that is better suited to Seville's high temperatures and adequate population habits (closing shutters so that heat cannot enter during the day, inactivity when temperatures are at their highest, vulnerable people habit of rehydrating themselves properly and avoiding activities that might put them at risk etc.).

Vulnerability reduction policies may therefore encompass adapting building techniques for new buildings, and - optionally - altering existing buildings, in order to address these events. It encompasses also alert and safety plans. Adapting homes and planning, means, on the one hand, promoting better heat comfort levels in buildings and streets (better protection from heat penetration) and, on the other hand, fighting the presence of urban heat island[3] (installation of road surfaces and roofs that reflect solar rays, city greening (Gill et al., 2007) etc.). Part of this adaptation can be undertaken at the building level (type and position of glazed surfaces for example), and part at urban area level, with urban planning choices (width and orientation of streets, parks and gardens etc.). Architecture and planning are very regulated and we should therefore not expect spontaneous changes by professionals or by households. It will be probably necessary to change standards, regulations and practices. Municipal authorities will have a crucial role to play in this area, in cooperation with other national and regional administrative bodies. In the academic world, questions linked to best choices for adapting cities to heat stress are at present the subject of intense research[4].

2.1.2   Illnesses range extension

Climate has an effect on the extension range of several diseases. For instance, in Europe some studies show that climate change may cause a northward extension of the range of several illnesses, notably Lyme disease (a parasitic illness transmitted by bites from ticks) and Leishmaniasis (a parasitic illness transmitted by mosquitoes and of which dogs are the main carriers) (IPCC, 2007a). This last illness is, at the moment, present in the Mediterranean region. In the same way, because of changes in the distribution of plant species, climate change may have an impact on the occurrence of certain allergies caused by pollens. However, these results remain broadly uncertain. The re-emergence of endemic malaria in Europe seems, in any case, to be very unlikely[5].

However, the opposite is true in developing countries which are particularly vulnerable to an increase in the range of several illnesses and especially malaria. This extension may indirectly impact European countries, by increasing the possibility of locally importing these illnesses. Finally we also need to note that higher temperatures may have an impact on food security, salmonella risk being, for example, particularly sensitive to temperatures (IPCC, 2007a).

These impacts are not urban in essence, but concentration of populations in cities make risks greater in urban contexts.

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[3]Cf. for instance Rosenzweig et al., 2009

[4]For instance VURCA, MUSCADE and ACCLIMAT projects, cf. http://www.cnrm.meteo.fr/ville.climat/?lang=en.

[5]Malaria was rampant in former times in Europe, on a large scale, and has been almost eradicated on the continent during the 20th century, especially thanks to progress in medicine, disinsectification and the drying out of marshes.
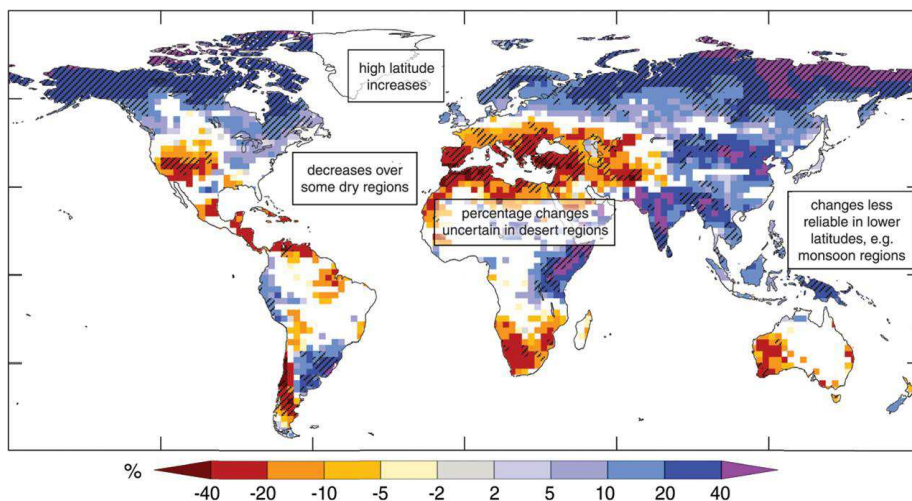
Figure 2.4: Large-scale relative changes in annual runoff (water availability, in percent) for the period 2090-2099, relative to 1980-1999. Values represent the median of 12 climate models using the SRES A1B scenario. White areas are where less than 66% of the 12 models agree on the sign of change and hatched areas are where more than 90% of models agree on the sign of change. Source: IPCC, 2007a.

2.1.3 Water resources

Climate change has an effect on fresh water availability across the world (Fig. 2.4). For instance, water stress will probably increase in central and southern Europe and especially in southern France. At European level, the percentage of areas suffering from intense water stress will probably increase by 19 to 35% in the 2070s and the number of people in water stress from 16 to 44 million (IPCC, 2007a). Beyond the quantitive problem (reducing of the quantity of accessible water), a qualitative one exist too: less water resources generally also lowers the quality of the water, since the dilution of polluting substances takes place in a lesser volume. Decrease of freshwater availability is a rather robust conclusion of climate models.

This impact is not particularly urban but it will be felt in towns and cities, especially in those already exposed to some extent to water stress. This impact will mainly be felt as a worsening of already existing issues, and a main vulnerability indicator is present day unsustainable use of water. Conversely, adaptation policies will consist in reducing water demand and resource pollution.

2.1.4 Air quality

Climate change may worsen local pollution, in particular in cities where some pollutants concentrations are large. Indeed some pollutants, such as ozone, are created by heat and sunlight acting on certain exhaust fumes. The increase in uninterrupted sunny weather in summer could then favor an increase in episodes of this sort of pollution. However, this risk is dependent on automotive traffic increase or decrease, and on vehicles exhaust fumes generation (for instance, increased modal share of electric vehicles could decrease pollution).

Similarly to impact on water resources, this impact will mainly be felt as a worsening of already existing issues. The impact will be especially felt in places with already high ozone pollution levels. Main adaptation policies consist in trying to reduce pol-

lution now (lessening of road traffic, replacement of older cars, regulations such as the creation of Priority Air Action Zones (ZAPA) in France, lowering of industrial emissions etc.) and its impact on the population (information on pollution levels, monitoring the population at risk etc.).

2.1.5 Migrations and tensions created by environmental impacts

These are indirect impacts created by other more direct consequences of climate change, occurring not necessarily in the same location. It can be for instance tensions within a country or between countries caused by the environmental impacts of climate change or from large-scale migrations caused by sea-level rise. An especially important case in developing countries is rural exodus acceleration due to countryside food-producing farming productivity decrease. This type of impacts is not very likely in developed countries.

2.2 Risks caused by natural disasters

In France, the most common natural hazards are floods, storms and clay soils expansion and contraction. Floods can be divided in two groups: coastal floods, which are likely to increase due to sea level rise (SLR), and inland floods, which risk may vary as a consequence of changes to precipitation patterns and watercourses runoffs. Here, again, impact is not just on urban areas. However, high concentrations of population and heritage, as well as the intricated way urban economies are organised, make these risks particularly difficult to manage in an urban environment. In France, because of growing urbanization, especially in risk-prone areas (cf. Section 1.1), these risks have greatly increased in the last few decades.

2.2.1 Sea level rise and coastal floods

SLR will have consequences in terms of material losses due to the slow submerging of the coast. It may also threaten human lives because of the increased risk of coastal flooding following storms.

Due to the melting of glaciers, to the progressive receding of ice in Greenland and Antarctic, and especially to the dilatation due to sea warming, it is estimated that ocean average level will rise during the coming centuries. The amplitude of this increase is difficult to determine but there is a strong probability that it will be between 20 cm to 1 m by 2100 even though there are more pessimistic projections in some of the literature (IPCC, 2007c). At the present time, a SLR of about 3 mm per year is already measured.

The impacts of such a rise do not come from the progressive rising alone, since this will happen very slowly. An essential consequence is the impact of the rise on tides and storm surges (cf Box). Permanent SLR due to climate change will widen the area that can be submerged in case of storm. It will also lead to an increase in floods frequency and intensity in areas already at risk. This effect will be all the more marked since climate change may well cause an acceleration in coastal erosion and therefore alter existing natural barriers to coastal floods (IPCC, 2007a).

Storm surge

Due to the local lowering of atmospheric pressure, and to winds which "chase" the seawater onto the coast, local sea level can rise during a coastal storm. This sudden rise in the level of the sea ("storm surge") can cause coastal floods and have serious consequences. Storm surge was up to 8m when hurricane Katrina struck Louisiana in August 2005 (Source: Center for the Study of Public Health Impacts of Hurricanes) and up to 1.5m (which added to the high tides) when the European windstorm Xynthia struck Vendée and Charente-Maritime, in France, in February 2010 (Source: SHOM).

Slow drowning of coastlines due SLR may cause significant losses. This phenomenon should not be analyzed in isolation, but added to that of the erosion, that we can see at present and which climate change may also influence. Erosion is a natural phenomenon of receding coastlines and is observed throughout the world but is one that is getting worse due to a variety of pressures, especially pressure from human activity. In France, for example, according to the Eurosion database (cited in ONERC, 2009a), one quarter of the coastline of the mainland (27%) is suffering from erosion while 44% is stable and only 10% in extension. The rest of coastline consists of coats that are artificially fixed (port areas and sea walls) or coasts whose properties have not been studied (respectively 17% and 5% of the coast line). Sandy coasts are more affected by erosion. An increased risk of coastal erosion from climate change is almost a certainty in France during the 21st century (cf. studies cited in ONERC, 2009a), as rising sea levels, wind, temperature, atmospheric pressure and swell can influence erosion occurrence and gravity. Low lying areas such as the Mediterranean regions or Vendée, Charente-Maritime, Nord-Pas-de-Calais and the Aquitaine regions are the most seriously threatened.

The OECD undertook a study (Nicholls et al., 2007) which compared the exposure of large port cities (more than 1 million inhabitants in 2005) to coastal flooding at the present time and for a projection for the 2070's, based on socio-economic development and climate scenarios (Fig. 2.5). The analysis suggested that about 40 million people (0.6% of the world's population or about 1/10th of the cities under consideration) are at present exposed to one in a hundred year floods. In financial terms the total value exposed in 2005 in all the cities under consideration was estimated to be 3,000 billion dollars, which corresponds to about 5% of world GDP in 2005. The United States, Japan and the Netherlands are the countries with the highest figures. By the 2070's, the total exposed population could triple due to the combined effect of the rise in sea levels, demographic growth and increasing urbanization (Fig. 2.5(a)). The exposure of assets would increase more than tenfold reaching more than 9% of projected world GDP for this period.

At global level demographic growth, socio-economic growth and urbanisation are the most important factors which are leading to increased exposure to risk. this is particularly true in developing countries, since areas close to sea level are often most urbanized. Climate change and erosion may accelerate this movement and considerably increase risk exposure growth (Fig. 2.5(b)).

In developed countries, such as France, demographic and economic growth is slower that in developing countries and the role of climate change and SLR in increasing coastal flooding risk is greater, and sometimes even dominates socio-economic effects.

Vulnerability to this impact will come from the geographical situation, and also from the type of development; it is essential to limit vulnerability, by avoiding implanting people and buildings in risk areas and to protect those that are already there, while
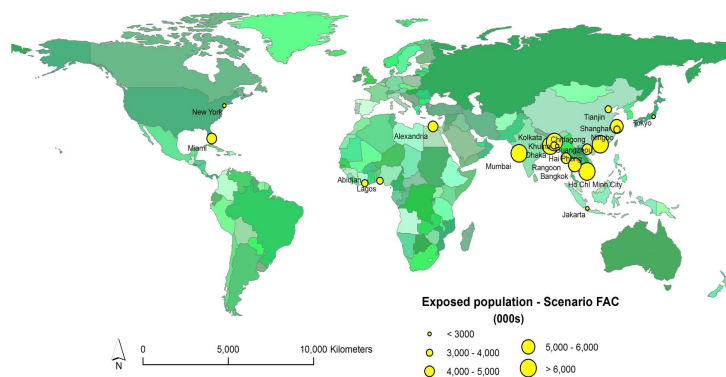
(a) Map showing the Top 20 cities for exposed population under the future climate change and socioeconomic change scenario
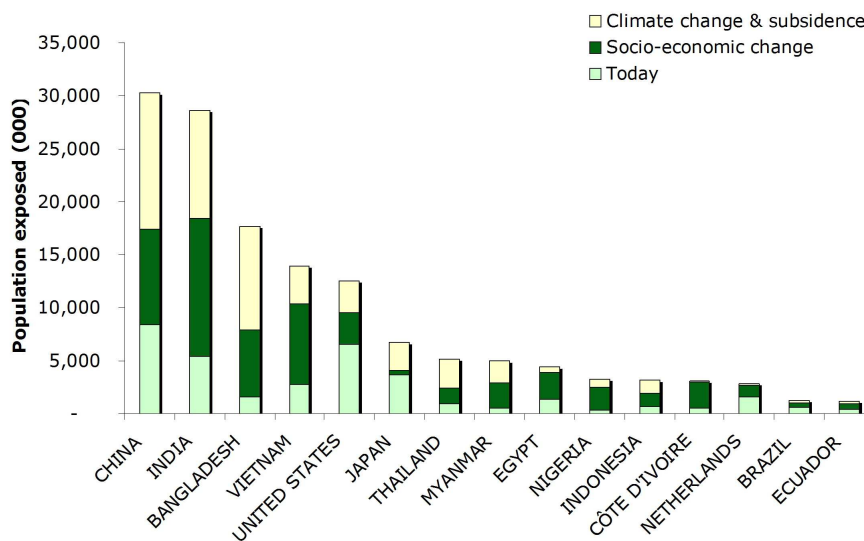
(b) Top 10 countries by assets exposed today and in the 2070s showing the influence of future climate change vs. socioeconomic change

Figure 2.5: Exposure of large port cities (more than 1 million inhabitants in 2005) to coastal flooding at the present time and for a projection for the 2070's, based on socio-economic development and climate scenarios. Source: Nicholls et al., 2007.

making sure that these defenses do not justify new installations, in which case exposure could increase.

Physical protections (e.g. dikes) are not generally considered to be sufficient when not complemented by land use policies. Although they may carry out their defensive role well, they may aggravate or create problems elsewhere (the solution to the problems of some becomes a problem for others). In addition in some cases, the construction of defenses may lead to an increase in vulnerability. This occurs when, from a false sense of security brought on by the defenses, new facilities are developed in the protected areas; the risk in these areas being never zero, this can lead to even higher losses if there is a serious climate event. It can therefore lead to an increased vulnerability. It seems more sensible to consider a prevention policy which limits the implantation of goods and people in risky areas, and protect what is already there rather than new constructions.

Some risk mitigation policies can also have negative side-effects. For example restrictive management of land may lead to an increase in its price with consequences for the cost of living and access to property. It can even lead to consequences in terms of investment in an area since businesses might prefer to locate to areas where the policies are less strict and where the price of land is lower. These consequences are complex and indirect; they depend on a number of factors about which local authorities have little say (for example national taxes or the economic situation). They will be studied in Chapters 8 and 9 in Part III.

2.2.2 River floods

Climate change will have a marked impact on flows in water courses, due to variations in rainfall pattern, snow fall and also to the shrinking or disappearance of glaciers. Dependent on geographical location, the risk from flooding might increase. It is quite difficult to make predictions on changes to flood risks and a large number of local studies are underway on this subject.

To the risk of flooding from water courses, particularly serious in urban areas, should be added the risk of flooding when rainwater drainage system cannot cope with the amount of rain falling. This risk is particularly great because certain climate projections include an increase in episodes of violent precipitation. In addition, ground cover impermeabilization reduces the capacity of the soil to directly absorb water and therefore increases flows the drainage system has to cope with. This risk is particularly high in areas where there are intense periods of precipitation, in tropical regions (Mumbai, Miami and Singapore where major investments are underway, for instance) and in the Mediterranean area.

Vulnerability reduction policies against this type of flooding are similar to those that aim to address coastal floods. The main vulnerability factor is the poorly controlled cities extension into areas at risk (See box on floods seen in the Gard Department, and see Fig. 2.6).
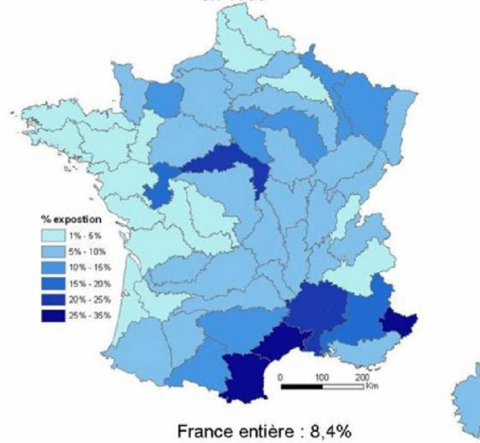
Figure 2.6: Number of individual homes in France exposed to a risk of flooding by catchment area in 2006. Source: ONERC, 2009b, after MRN, MEEDAT, INSEE, and SANDRE.

Floods in the Gard Department

The flooding seen in the Department of the Gard on the 8 and 9 September 2002 was considered by Ministry of Ecology and Sustainable Development inspection team to be "a very serious event, rare but not exceptional". The extent of material damage (1.2 billion euros) was about double that of previous events of the same type. This conclusion is explained in large part by the number of less than thirty year old buildings situated in flood-prone areas (this was the case for Aimargues and Gallargues-le-Montueux) or behind defenses that were breached or submerged by the flood (as in Aramon). An estimate made by the Languedoc-Roussillon regional environmental body (DIREN) using a 2001 map of flood-prone areas and the population census of 1990 showed that in the entire region, except in Lozère sub-region, one in six of the 384,000 inhabitants lived in flood-prone area. 321,000 were in areas with a high or very high risk of flooding (i.e. water level higher than 1 m and/or strong water flow during the highest flood recorded). Source: Trocherie et al., 2004.

Defensive systems, although they might be able to protect what is already there, are far from being the best solution (cf. Section 2.4.3). Urban sprawl, by extending artificial surfaces, also hampers the filtration of rainwater into the soil and increases the risk of flooding elsewhere in the same catchment area. To this should be added to the risks in built up areas caused by the size of the drainage system which will need to be able to cope with the most extreme weather conditions.

2.2.3 Contraction and expansion of clay soil

Clay soils expand and contract depending on how much water they hold. When subsidence under a building or infrastructure is not uniform[6], large amount of damage can be caused to the structure, especially if it does not have deep foundations. Damage to assets is often considerable and irreversible, and may require the destruction of

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[6]For example, when the soil under a building does absorb water and dry out at the same rate as the surrounding soil.

structures. Detached houses are particularly vulnerable to this, due, especially, to their foundations not being very deep.

Since 1989, in France, there have been almost 15,000 municipality, spread over 89 geographical departments,[7] that have been declared disaster areas due to this phenomenon. According to the French National Reinsurance Fund (Caisse Centrale de Réassurance), if in 2003 all municipalities asking for their area to be considered as having suffered from a natural disaster had all had their requests agreed, the total cost might have reached 3.5 bn € (1.3 bn € was actually paid). This would have been more than the sum of all costs associated to French droughts for the period 1989-2002 (3 bn €) (ONERC, 2008, 2009b).

A rise in temperatures and intense precipitations are all favouring contraction and expansion of clays. Predicted climate change might provoke the occurrence of both of these phenomena. In France, according to research and the various studies undertaken, an increase in the risk of the contraction and expansion of clays as a result of climate change seems almost certain during the course of the 21st century (ONERC, 2009a).

Depending on the nature of the soil, some regions will be more affected than others. Places already affected by this phenomenon, and therefore those with more clay soils, will feel this effect of climate change most strongly. Reducing vulnerability against this phenomenon requires a stricter application of the current building regulations for new-builds. For existing buildings the first step is the development of evaluation tools to assess vulnerability.

2.2.4 Storms

Studies suggest that, in temperate latitudes, storm intensity should not increase or not by very much (IPCC, 2007a). Damage linked to strong winds should therefore not change. However, rising sea levels could make these same storms more destructive, due to increased coastal flooding (see Section 2.2.1).

2.2.5 Other types of disaster

Other problems are likely to occur due to climate change: forest fires, avalanches, land slides (besides those created by erosion and clay soils), technological accidents, for instance as a consequence of a natural hazard. The impact of climate change on these events is however not well understood.

Forest fire is of importance for urban areas, especially those where peri-urbanization is strong, leading to an increase in the number of houses in direct contact with a forest. This is for instance the case in several cities in the south of France. Overall the population is now more vulnerable to fire than in the past and this trend seems set to continue (ONERC, 2009a). The consequences for urban areas can be illustrated by recent events in California and Australia (Source: Emergency Events Database, CRED[8]). Australian bush fires in 2009 affected almost 10,000 people and caused over 180 deaths and economic damage of 1.3 billion dollars. In Los Angeles, fires caused losses of 2 billion dollars in 2008 and 8 dead and 2.5 billion dollars losses in 2007. In this case it was the fact that forest and buildings were embedded together that made the fires so dangerous, and so difficult to manage for emergency services.

However, it is not possible be certain whether the number of forest fires will increase in the future. Higher temperatures and more frequent droughts are evidently

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[7]France is divided in 101 geographical departments, and 36682 municipalities.

[8]Centre for Research on the Epidemiology of Disasters http://www.emdat.be/.

factors that will increase the risk. Conversely, vegetation pattern changes (or even forest disappearance) could limit risk level (cf for instance CGEDD, 2010, for a study in France).

2.3 Risks on economic activities

2.3.1 Energy consumption variation

Because of temperature change induced by climate change, the consumption of energy for heating and for air conditioning will certainly vary. These changes will not happen only in urban areas, but, as today most of the population lives in towns and cities, changes in urban areas are of great importance when looking at the size and management of energy infrastructures. In addition, urban phenomena, especially UHI, interact with the regional climate to determine energy consumption patterns evolution.

The demand for heating in winter is likely to decrease, and that for air conditioning to rise. According to some climate scenarios it is projected that, towards 2050, in the Mediterranean basin each year there will be, on average, a decrease of 2 to 3 weeks of heating days and an increase of 2 to 5 weeks of air conditioning days. As a consequence the peaks in demand for electricity may, in some areas alter, move from winter to summer (IPCC, 2007a).

This might, in some cases, happen in a context of difficult electricity access (and therefore lead to higher prices or power cuts). Indeed, electricity production is very dependent on water resources. for instance, an increase the temperature of water courses and lakes could affect cold water sources for nuclear and thermal power stations. The decrease of water reserves in dams in summer would have an effect on hydraulic power production. Changes in demand for water, other than in the energy sector, could increase this phenomenon by multiplying usage conflicts, especially with farming and tourism. Finally, expected changes to the climate could also have an impact on the production of other renewable energies.

If the impact on electricity production is greatly uncertain, an increase in energy consumption pattern change is relatively certain in some regions, for instance in areas in the south of France.

2.3.2 Impact on tourism

Tourism is an important economic activity for a large number of French towns and cities and also justifies a certain level of infrastructure, such as accommodation (hotels and camp sites), transport (rail networks, stations, road and motorways etc.) and energy infrastructure. Future changes to tourist demand in a region may have major consequences on current infrastructure choices and on economic activity, in cities and in rural areas.

The attractiveness of a tourist destination is the result of many factors, and many of these are linked to climate. Some are directly linked: numbers of sunshine days and mean summer temperatures in summer, snowfall for ski resorts etc. Others are indirect; quantity and quality of available water, natural habitats and landscapes in the different seasons when considering nature tourism etc.

In 2005/2006 the French Tourism Authority commissioned an exploratory study on the potential impacts of climate change on tourism in France (Dubois and Ceron, 2006, see also INSEE, 2008; ONERC, 2009a). This study looked at the vulnerability of a

number of branches of this activity in France. One of the more vulnerable activities appeared to be skiing and winter sports, especially at lower altitudes. Indeed, this activity is very sensitive to projected decrease in snow cover (this decrease will happen with a high level of certainty: in Alpine region, it was computed that snow cover duration will be reduced by several weeks for each degree of temperature increase) (IPCC, 2007a).

Summer tourism may also be impacted, especially through a decrease of water resources. Tourists habits, such as the infrastructure they use (accommodation, green spaces, leisure facilities such as swimming pools, golf courses etc.) generate water consumption, which even if lower than other economic activities, cannot be excluded from water management issues and debate. Tourism use of water is especially intense during the summer when the resource is scarce and required for other purposes (irrigation etc.). It is often located in places with limited resource (islands, mountains etc.). Access to lakes and rivers, which contribute to the landscape or are the basis for activities (bathing, sailing etc.) can be dependent on climatic context. For instance, fishing in fresh water can be forbidden in case of high temperatures (it happened during the 2003 heatwave in France, for example) etc. Decrease in flows and water level can favor eutrophication and various pollutions which can impact tourism. In France, the Mediterranean zone might be the most impacted. Water availability variation is projected with a high certainty level, and impact on tourism has the same level of certainty.

Climate change may also impact tourism through its consequences on ecosystems. Water stress and forest fires generated buy climate change that may go with it could lead to consequent changes in patterns of vegetation and alter the landscape.

Discomfort due to heat caused by an increase in summer temperatures may also have a strong influence on tourism, especially in large cities where temperatures will be increased still higher by UHIs. This discomfort may lead to variations in overall tourist activity[9] and a redistribution in the timing of tourist activity (increase in tourism in the spring and autumn for example). Exposure to the health risks that have been detailed above could translate into a redistribution of touristic attendance, depending on the place, season, client segment (older people for example).

The impacts of climate change on tourism are therefore very varied and policies to reduce vulnerability will depend on the impact considered. However, most of them will encompass a reduction on current vulnerabilities. For instance, ecosystems adaptation can be improved by reducing present human-induced stresses. Similarly, water resources decrease will be less problematic if the overall demand for water begins to be reduced now.

2.3.3 Changes to French migratory flows

Another consequence of climate change may come from changes to migratory flows. For instance, in France, until now, the southern part of the country has been in overall more attractive than the north (Baccarini, 2007). A slow migration of population from the north to the south of the country can be observed. This trend may change, especially for older people, because of the heat waves in the south, which climate change may exacerbate. This may have multiple long-term consequences on local economies. Demographic projections for French departments and cities may have to take into account the impact of climate change on attractiveness and therefore on migration. Towns such as Montpellier, that have a desirable climate, are growing fast at present but, if

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[9]In France, this could lead to an increased touristic attractivity in the north, the west and in mountain areas since they are cooler.

they see their attractiveness reduced they may need to invest to compensate for this loss (air conditioning in public transport, planning and architectural changes etc.).

2.3.4 Spread of economic losses from one sector to others, and the particular roles of networks (energy, water, communication and transport).

Because cities are integrated systems with complex, extended and various links, any impact affecting one part of a city will indirectly affect all other parts. For example, less tourism will generally mean there will be less economic activity in a number of other economic sectors (for example services to businesses or property). In the same way, a flood may have serious direct consequences due to the damage it causes (roads, homes, factories destroyed), but it will also have indirect consequences: temporary breaks in communications or electricity supply caused by a flood may have very high economic costs and affect areas that have not been directly flooded.

Networks are an important element of this vulnerability: transport, water management (drinking water and water purification), energy (electricity supply, heating and cooling networks) and communication networks. A modern city cannot function properly, as a whole, unless each of these networks works perfectly. Any interruption or lowering in performance of public transport or electricity supply can easily paralyze or handicap all economic activity (see below for a study on the impact of climate change on the Boston Metro system). A purely sectoral approach is therefore unsuited to an examination of impacts within an urban environment, and systemic studies are necessary. They show the importance of these indirect effects and how important it is to take them into account.

For instance, about 30% of recent California earthquake losses were related to transport issues, with employees unable to reach their workplace, and clients unable to go to commercial zones (Tierney, 1995).

Evaluating these indirect losses is the subject of a number of research projects. It is impossible to reproduce all the socio-economic mechanisms at stake, but these studies are trying to include as many number of indirect effects as possible. Often these works concentrates on the role of transport infrastructure and electricity and water supplies. All these studies show the importance of these indirect effects and how important it is to take them into account. They all conclude that the indirect costs are responsible for a large part of the total cost of these natural disasters. Below are the results of some of these studies, looking at flooding, earthquakes or power cuts (they are cited in Hallegatte et al., 2010)..

When the Northridge earthquake occurred, near Los Angeles in 1994, the indirect losses amounted to 25 to 30% of the total losses. Following the 1994 earthquake, a total of 69,000 unemployed people.year was caused by firms stopping their activity (Cho et al., 2001). About half of this unemployment occurred outside of the area that had suffered material losses. Broken supply lines, caused by the earthquake, were the origin of most of economic activity interruptions, before interruptions caused by direct destruction (Tierney, 1995). About one shop in four was affected by delivery problems in goods and services due to the earthquake. On average, all shops were closed for two days following the earthquake. Direct damage caused to buildings was only one of the causes of closure, and was cited in only 32% of cases.

Indirect economic losses in Louisiana after Hurricane Katrina have similarly been assessed to 42 billion dollars as compared with 107 million dollars in direct damage

(Hallegatte, 2008). The model used shows that indirect losses increase in a non-linear fashion as compared with direct losses, which suggests that there is a threshold in the capacity of the economic system to adapt. In the case of Louisiana, indirect losses remain negligible if direct losses are less than 50 billion dollars, but increase very quickly if they are greater. When direct destruction amount 200 billion dollars, indirect cost reaches the same figure.

In vulnerability evaluation, it is essential to look at the risks for nodal points such as hospitals (because risks linked to transport and the evacuation of patients are important), emergency services (some fire stations are in flood-prone areas, which might paralyze a response to an emergency) and decision making centres.

A number of local characteristics can mitigate these indirect effects (Kroll et al., 1990; Webb et al., 2002): diversification of the economy, a redundant transport network, and resilience service, for instance, a very brief closure of municipal services, have enabled to greatly limit Loma Prieta earthquake (California, USA, in 1989) consequences on the local economy.

In urban areas a particular problem is the evacuation in the case of imminent danger. The case of New Orleans and Hurricane Katrina shows what difficulties might be faced. First of all, transport infrastructure may be inadequate for the rapid evacuation of the population, which means that any evacuation needs to be better anticipated which in turn may lead to a higher risk of a unnecessary evacuation if there is a false alert. Very densely populated areas, and therefore large urban centers, are naturally particularly difficult to evacuate. Then particular attention needs to be paid to the various categories of vulnerable people who are often concentrated in certain districts. These people may lack information or means of transport, or be vulnerable to the risk of burglary and looting. Persons with reduced mobility, older people and the sick often find it difficult to leave their homes without external support. Finally, insufficient understanding of the risk, evident in those areas that are rarely affected, is a crucial risk factor[10].

2.3.5 Combination of sectoral impacts

All the sectoral impacts that we have listed should not be considered separately. Climate change will compound the effects of all impacts, probably in parallel. This combination might create increased problems, for example if a decrease in water resources occurs at the same time that an increase in the frequency of heat waves, or if a reduction in tourism occurs at the same time that a need in in coastal defenses investment. The total impact on the economy might therefore be much higher than the sum of the parts.

Climate change is not the only challenge cities need to prepare for, and other challenges have to be taken into account. Adapting to climate change will need to be undertaken alongside measures aimed at reducing GHG emissions, which will create not only areas of common interest but also areas of conflict. There may be conflicts on the policies themselves (when a measure helps to adapt but increases emissions, or the opposite), or on resources (when investing in mitigation and adaptation at the same time goes beyond the total investment capacity).

Beyond environmental aspects, in France, it is possible that the population, and therefore the urban population in cities, decrease significantly in the second half of the 21st century which would be a large shock to urban dynamics. East Germany is an example; there population decrease in towns is a widespread phenomenon and shows how difficult it is to manage towns with declining populations. Problems specifically

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[10]That was for instance clearly seen during the Xynthia storm in France

linked to climate change mays therefore have to be managed in a very different context from the one we know today.

This combination of factors will have important consequences. Even if each sectoral impact could be managed and controlled separately, the management of a combination of simultaneous impacts in multiple sectors, alongside other urban challenges such as a reduction in population, could be much more difficult to deal with. It could come up against the limits of a local authority's ability to cope (in terms of availability of funds for investment, technical ability and competence and attractiveness). At present there is no exhaustive analysis of the impacts of climate change on a city or region and it remains difficult to judge the difficulties there may be in overcoming impacts.

2.4 Adaptation at city scale

It is now becoming clearer and clearer that local level is of great importance in climate change adaptation policies, as it is in mitigation policies (cf. Section 1.4.2). The impact of adaptation policies is often felt at local level and generally depends on the particular characteristics of an area; its topography, economic structure, the ability of households to adapt etc. The best adaptive policies therefore differ from one place to another and should be specifically designed for that area.

Scaling at town or city level is useful because this scale is not too small: towns and cities are powerful players, they have the means to put ambitious policies into action. This scale is not too big either: towns and cities are very integrated systems in which the various networks (water, electricity and transport), the economic make-up and the social fabric are embedded and work together.

2.4.1 Main risk factors, and adaptation policies

First let us sum up the main vulnerability factors; unsuitable planning and built environment (heat stress, energy consumption), unsuitable defensive work and extension of the built up area into areas at risk (flooding), widespread pollution and non sustainable use of water supplies, (diminution of water resources and impact on tourism), poor protection of sensitive natural resources (tourism), building regulations poorly enforced (contraction-expansions of clay soils), inadequate diversification of the economy and vulnerability of networks to impacts (indirect economic impacts).

A number of measures that aim to reduce vulnerability to climate change first try to reduce vulnerability to the current climate and its changeable nature, especially as regards current extreme events; adapting to climate change means first adapting to the current situation. In large part climate change acts by increasing problems that exist already, and, leaving aside most notable extreme events, climate change is rarely the main threat on sustainability. It is therefore possible to imagine measures that adapt to climate change by modifying, at the edges, measures designed to reduce the existing risks (for example putting higher sea walls in place to defend built up areas on the coast). Other measures may however become necessary when the change in climate becomes more serious. If this becomes the case, then the review of existing vulnerabilities will become insufficient to construct an adaptation strategy and specific measures will need to be put in place to counter new potential threats.

In the short-term it would be useful, in the first place, to examine the origins and evolution of the vulnerability. The increasing risks that we are now seeing and which

explains the increase in losses linked to natural disasters have precise causes, linked to current socio-economic changes:

- lack of land leading to building on flood-prone areas, intensified by an increase in the number of households and the development of detached houses that are occupying more land

- migration of people southward where risks are higher

- spatial inequalities and social segregation, which concentrates problems in certain areas and may push the more fragile towards areas at risk.

- the cost of risk mitigation policies, evident in the case of policies for the construction of defensive infrastructure but equally evident in almost all other cases; as for the example the constraints on new buildings which have a high economic and political cost (especially at the municipality scale)

- Lack of political will, except in the few years that follow a disaster.

- Loss of the safety reflex (like not living on the ground floor in flood-prone areas) and a poor risk awareness (not listening to advice in the case of an alert) despite recent developments (like the "vigilance"map produced by Météo-France for example).

To control the current increase of risk and adapt to climate change we first need to address these problems. Then measures can be amended to take account of climate change. Some ideas for adaptation are developed below. These consist mainly of investment and changes to standards and regulations. As stated in Hallegatte et al. (2011b) the production and supply of information has also an important role, but these issues are not specifically urban.

There is rarely an optimal adaptation option. Often the most appropriate adaptation strategy depends on political and social policies and on the vision a region or city has of its own future. Ideas suggested here should be considered as being part of an adaptation toolbox, and the choice of measures remains a political decision deserving a large public debate (Hallegatte et al., 2011b).

The costs of adaptation are relatively smaller when policies are anticipated[11]. There is a tradeoff between implementing policies late, hence with a high cost but with a sense of urgency, and an early implementation, cheaper, but undertaken without any sense of urgency and therefore with a higher political investment (cf. Chapter 3).

Let us do now an analysis of four categories of policies : changes to land use and town planning (Section 2.4.2), direct investment (Section 2.4.3), adaptation to heat waves (Section 2.4.4) and resilience increase (Section 2.4.5).

2.4.2 The key role of urban planning

Because these places were more easily accessible, many cities have been built along watercourses or by the sea (Lall and Deichmann, 2010), and many city centers are therefore in flood-prone areas. For instance, low lying coastal areas exposed to cyclones and coastal flooding cover 2% of the world's surface but are home to 10% of the

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[11]It is cheaper to build oversized defenses than have to make them larger later, it is cheaper to designate an area as unsuitable for building, than have to re-locate those in an already inhabited area etc.

world's population, and, importantly, 13% of the world's urban population (McGrana-han et al., 2007, see also the number of large cities located near a large water body, on Fig. 1.2 in Chapter 1).[12]

Although the historic centers are in general situated away from areas at risk, recent extensions to town and cities have created heavy pressure on land in these areas leading to larger and larger proportions of the population and the local economy placing themselves at risk. It is a classic scenario found in several cities around the world, from New Orleans to Shanghai. In France, this progressive urbanization of risk-prone areas is increased by urban habitat density decrease, related to the greater number of detached houses: each household is occupying more space than before, land becomes scarcer and prices rise which leads the next arrivals to live in riskier areas.

This explains, in part, why growth in the number of homes in flood-prone areas has accelerated in France over the last fifty years; between 1999 and 2006, there was an increase of 7% in the number of homes build in flood-prone areas, which is almost 100,000 extra homes in 424 municipalities of more than 10,000 inhabitants which are now at high risk of flooding (Laporte, 2009). In some areas, this urbanization is increased by the presence of amenities which attract people to live in areas at risk, such as a view over the sea or having a river nearby (see for instance the box about flood management history in New Orleans).

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[12]Similarly, because these places were rich in rich in natural resources, many cities have been built in regions with fertile volcanic soil, but with high risk of eruption (cf. for instance Small and Naumann, 2001).

Flood management history in New Orleans

New Orleans was funded in 1718 and became in the early XIXth century the largest U.S. city in the South. Because the area protected by natural levees was very small, most of city developed on natural marshland, artificially dried using pumps, drainage canals, and artificial levees. From the beginning of the XXth century, the use of more reliable electric pump and the development of the levees allowed for an accelerated development of the city. From then, however, New Orleans has been flooded four times in spite of its protection system, in 1915, 1947, 1965, and 2005. In 1915, it was a category 4 hurricane that impacted the city and overflows the protection system along the Lake Pontchartrain coastline. Water levels reached 13 feet in some districts, and it took 4 days to pump the water out of the city.

Following this event, pump stations were upgraded and levees were raised along the drainage canals. In 1947, a category 3 hurricane made landfall on the city and the Lake Pontchartrain levees failed. Thirty square miles were flooded with water level reaching 6 feet, and 15.000 people had to be evacuated. Like in 1915, major improvements were made on the protection system in the immediate aftermath of the disaster, with raises and extensions of the levees. In 1965, however, hurricane Betsy (category 3) made landfall on New Orleans and flooded the city again. About 13.000 homes were flooded, leaving 60,000 homeless, 53 deaths, and more than $1 billion of losses.

This event leaded to the Flood Control Act of 1965 in the U.S. Congress and to an ambitious plan to protect New Orleans. This plan was supposed to be fully implemented within 13 years. Facing difficulties, including conflicts with environmental protection, the plan was stalled, however, and finally revised into the "high level plan", which started to be slowly implemented in the mid-80s and was considered to be between 60 and 90 percent completed when Katrina struck in 2005. The complete failure of the protection system in 2005 demonstrates that both construction and maintenance have not been adequately supervised and monitored.

What is striking in this series of disasters is the systematic implementation of ambitious protection upgrades after each disaster, but the absence of long term action about risk management.

Source: Hallegatte, 2010

Land-use is therefore a crucial component of adaptation and risk management policies, in order to contain new developments in areas where flooding risk is too high (that is a decrease in the exposure, if we follow the definition given in introduction).

However it is impossible to stop all new building in flood-prone areas, and a zero risk does not exist. In addition, the impact of restrictions on building would lead to an increase in the price of land which would be a problem for ordinary people and especially the less well off. Intermediate solutions therefore need to be found for areas where flooding is a possibility but would be exceptional. In these areas building would need to meet certain standards which would limit the risks and so reduce vulnerability as defined in the introduction. This would require; avoiding one storey buildings that do not allow people to take refuge on an upper floor if there is a flash flood, placing services (such as electricity) above homes so that they would not be affected by a flood, use building materials that are more waterproof or even put homes on stilts or make evacuation mandatory in case of a flood alert.

As a general rule, encouraging greater density allows to concentrate development in safer areas and therefore avoids building in areas at risk. Planning regulations in safer areas will have an impact on the risk of flooding, which demonstrates the importance of a systemic approach to the management of risk and spatial planning.

Planning regulations do not just concern areas at risk from flooding; they also influence, for example, the permeability of the soil which has an influence on flooding risk.

2.4.3 Defensive infrastructure and other direct investment

As has already been mentioned, defensive infrastructure - like seawalls and dykes - are important for the prevention of risk and therefore climate change adaptation. In particular, seawalls and dykes are vital for the protection of densely populated and urbanised areas, at a relatively low cost. However building defenses implies (1) regular maintenance, the absence of which may lead the defense to increase vulnerability, and lead to dramatic loss of life (ii) a planning document which clearly highlights the protected areas, to ensure that the defence does not attract investment and people to an area at risk (iiii) an alarm and evacuation system, since a defence can always be breached or overcome by the intensity of a natural disaster.

The construction of defenses should only be considered when it is one of the components of a larger risk management plan that includes the maintenance of the defense system, building restrictions in the non-protected area and a warning and evacuation plan.

In addition, the defense approach is not necessarily the best and it is important to take into account its negative impacts. First defenses lead to an artificialization of the structure and shape of a coast or riverbed, with consequences for the landscape and biodiversity. For example sea wall and dykes which protect the coast against flooding may, in some cases, contribute to the exhaustion of fish stocks by destroying their ecosystem (Clark, 1996), 90% of fish species depend on coastal areas at one moment or another in their life cycle (this secondary impact leads also to monetary losses because of its impact on the fishing industry). Attractiveness of altered areas may be decreased with an impact on recreation and tourism. Finally protection of an area might increase risk on another part of the coast or downstream of a river. It is therefore important to be careful not to simply transfer the risk, and to work at a sufficiently high spatial level to be able to take in all the effects of protection.

Defences are not the only investments that might potentially be required when facing climate change. The upgrading of water management systems - and especially drainage and water treatment - will equally be necessary; in particular in areas that are subject to high rainfall (the South of France is included in this). Other infrastructure may also require direct investment; improvement of roads and transport infrastructures, moving and/or burying of electric cables etc.

2.4.4 Adapting the built environment to higher temperatures

Changing climate conditions will probably call for changes in town planning and architecture. In a number of towns and cities in southern Europe and the Maghreb, traditional buildings are suited to high temperatures with narrow and shady lanes which stay cool, patios etc. Climate change impacts may create an incentive to use these skills, and to export them to other parts of the world. For instance, the traditional practices that we find in Spain and in North Africa may be found to be useful for France at the end of this century. Recent studies have tended to demonstrate scientifically the beneficial effects of the traditional house in the fight against those risks caused by heat waves (for example Shashua-Bar et al. 2009).

In warmer climates modern extensions to towns and cities are often more sensitive to heat stress like: building blocks built in the nineteen seventies, air-conditioned office towers, wide avenues that allow traffic to circulate. This "loss" of traditional skills often has a cultural as well as economic basis; the need to allow cars to flow through the city, standardised construction techniques used on modern buildings that are cheaper than traditional techniques etc. It is therefore not easy to use again the traditional techniques.

Adaptation of the built environment poses new questions because of the cost of this adaptation and the time required for a transformation to be significant and have a visible impact. We need therefore to ask ourselves whether we should change standards for new buildings only or insist on the refurbishment of existing buildings. In the case of refurbishment, timescales will be important; the quicker the adaptation is undertaken the costlier it will be (and pose manpower and training problems); we will definitely need to start as soon as possible so as to be able to undertake this transformation at a sufficiently slow pace to make it possible economically.

If this adaptation is undertaken correctly it could also provide some important side-benefits; accelerated refurbishment of homes in a poor state of repair, reduction in energy use from heating, improvements in the quality of life of the population.

2.4.5   Increase in urban resilience

Towns are likely to have to face a number of shocks linked to climate change, whether they are extreme events like storms or job losses due to changes in tourist flows. In addition to strategies that aim to reduce the vulnerability of these shocks (adaptation of the built environment, modification of infrastructure etc.) it should be possible to try and increase the overall resilience of the area.

This might be done by diversifying the local economy; for example a town that is dependent on tourists or fishing might try to create additional job opportunities which do not have the same vulnerability as existing activities, in order to lessen the risk that all local jobs will be affected by the same shock at the same time. In addition towns and cities, being very vulnerable to an interruption in networked services (transport, communications, energy), could work on the redundancy of these networks.

Towns and cities could also put in place specific tools which aim to help local people and businesses face up to shocks whether they are regular or spread over time. These may be bodies giving information on those local impacts that might be expected from climate change to local deciders, or mutual support systems or insurance.

One of the strengths of strategies that aim to increase resilience is that they bring benefits,that may go way beyond adapting to climate change, by reducing the general vulnerability of a region.

2.5   Conclusion: vulnerability reduction in practice

Today it is impossible to calculate the future costs of climate change for cities or to guess the sums we will need to invest in adaptation. However, the scientific literature makes it clear that adequate adaptation policies, put in place sufficiently early, would be able to very significantly limit the total impact of climate change.

This chapter has several conclusions. First, towns and cities are vulnerable to climate change, but climate change impacts are often an amplification of already existing problems (for example flooding, or local pollution). This suggests starting with implementing no regrets adaptive measures. They enable to improve the existing situation

in towns and also generate interesting side benefits at the same time by reducing future vulnerability to climate change.

Other measures could nevertheless become necessary when changes to the climate become larger or when long term measures become necessary. The review of existing vulnerabilities will become insufficient to construct an adaptation strategy and specific measures will need to be put in place to counter new potential threats.

Because of cities evolution inertia, some of these measures will have to be enforced early enough, which is especially the case for measures involving large planning schemes which have irreversible long-term implications. For policies which anticipate events, taking into account uncertainty about future climate change is vital and there will need to be coordination between the various players.

Second, the present vulnerability of cities can be explained by unfavourable socio-economic and demographic changes (migration towards areas at risk, lack of available land, overconsumption of water etc.) to which specific responses need to be made; rather than just looking to reduce risk, we need to consider the factors that explain the increase in risk and attack their original causes.

Finally, one of the particularities of cities is the way they function as systems, which means that adaptation strategies need to be designed in an integrated way that takes into account combined impacts in the various sectors and areas as well as other political and economic objectives (Bulkeley et al., 2005).

When drawing up a policy to reduce vulnerability it will be necessary to work on a very large canvas, which takes into account multiple factors and objectives. Adaptation can only take place on a case by case basis for each area, taking into account the secondary effects of the measures, whether positive or negative, their costs and local political choices.

Issues surrounding the design of adaptation strategies are to some extent similar to issues surrounding mitigation (cf. Section 1.5) : city evolution inertia will play a major role, with a choice among short-term and long-term policies, among which urban planning. The choice between policies is made extremely difficult by side-effects, which are in some case rather obscure, and make a cost-benefit analysis difficult. Long-term policies appear potentially very efficient, but uncertain, because related to unknown future evolutions. Another issue should be added : adaptation and mitigation policies often rely on the same tools (the best example being urban planning), leading to synergies, and to conflicts, and should therefore be drawn up in a consistent way.

These issues will be studied in more details in the following chapter, and in Part III we will show that integrated city modelling can help address these issues.

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Chapter 3

Research problem

*Urban areas, home to more than half of the world's people, are emerging
as the 'first responders' in adapting to and mitigating climate change.*

Rosenzweig et al., 2010

As presented in chapters 1 and 2, cities are important actors of two different issues
global greenhouse gases emissions and climate change vulnerability. Many key drivers
of both issues are similar, and driven at the municipal level, such as land use planning,
urban transport, housing or urban disaster risks policies. Our thesis in this work is
that three obstacles, at least, make using these tools extremely difficult for both issues.
Following boxes present practical examples of choices which illustrate them.

First, because of high inertia of city built structure, anticipation is required if one
wants cities to be adapted to the climate of the end of the century and to contribute less
to global CO_2 emissions within a few decades: it is necessary to start now to change
building design and urban planning habits (Section 3.1).

Second, anticipating is difficult, because the impacts of policies depend on several
external factors: demographic, socio-economic, cultural, political and technological
changes will play a major role (Section 3.2). For instance, success of strategies aiming
at reducing transport energy consumption is dependent on future transport prices and
technologies.

Third, as adaptation and emission reduction policies often rely on the same tools,
synergies and conflicts exist. Urban climate policies are also not developed or imple-
mented in a vacuum; they interact with other policy goals, such as economic competi-
tiveness or social issues, making their design more difficult (Section 3.3).

This chapter will present the relevant results found in the literature on these issues.
We will develop a tool in Part II which will enable us to further investigate into these
problems, and in Part III we will use this tool to draw some conclusions.

Should we favor compact or spread-out cities?

Urban shape plays an important role in GHG emissions (cf. Section 1.4.1 in Chapter 1), however in practice, no clear advice can be given to urban decision-makers concerning this issue.

It is a good illustration of the three obstacles we will present :

- *First, urban shape evolve very slowly, and immediate action is required for the cities to have climate-friendly forms within a few decades. This is especially the case in rapidly-growing developing country cities.*

- *However, there is no clear indication whether high-density or low-density development should be favored. Dense and compact cities are generally considered as more environmentally-friendly than low-density spread-out cities, especially because of potentially lower transport-related GHG emissions and loss of arable land. However, low-density cities may enable larger decentralized renewable energy production in the city (e.g. photovoltaic panels on roofs), which may counterbalance transport-related increased energy need (Section 1.4.1.1 in Chapter 1). Future transport and renewable energy production technologies, future lifestyles (e.g. massive development of telecommuting) may decide what will be the best solution, but their potential are so far unknown.*

- *Dense cities might also increase incentive to live in flood-prone areas and make heat-island effect stronger because of the lack of vegetation. Urban sprawl containment may also increase real estate prices and, in some transport technology evolution scenarios, pollution level. Interactions with climate change impacts vulnerability, and with non-climate policy goals cannot be neglected in reflexions about optimal urban forms.*

The model we present on Part II, and the analysis we carry out in Part III is a first step in addressing these issues, and understanding which policies impacting urban shape should be implemented, according to decision-makers goals.

> **Should we favor renovation or destruction?**
>
> *Cities GHG emission and vulnerability to climate change are greatly determined by infrastructures (cf. Section 3.1): residential, commercial and publics buildings, transport, water and energy infrastructures etc.*
>
> *When existing infrastructures are not "climate-fiendly", i.e. not adapted either to low-emission lifestyle or to future climate change impacts, one question exist whether they should be retrofitted, or simply destroyed or abandoned to build new ones. This is for instance the case with residential buildings with bad insulation, or with buildings in flood-risk zones, or with low-density neighborhood where public transport would not be possible to develop.*
>
> *Cost plays an important role regarding this issue, but it is not the only important factor. This is another good illustration of the three points of our thesis:*
>
> - *Capital lifetime will be a key element, as shortening live-time of an infrastructure to build later a new, more adapted one may be more cost-effective than early retrofitting*
>
> - *This decision will depend on future technological change: it may be worth waiting for cheaper technologies than retrofitting now.*
>
> - *Finally, side-effects of existing infrastructure are important: promoting home renovation to reduce heating related GHG emissions enables to decrease energy bill for poor households. Low-density neighborhood may be related to decreased quality of life (e.g. Brueckner and Largey, 2008; Renard, 2010), so active urban densification may be useful. Here also, the tools we propose can help decide about urban choices.*

3.1   Inertia and cost of delays

Although climate change mitigation and adaptation policies demand a high level of investment, the costs will be even higher, the longer the decision to act is delayed.

Climate policies (adaptation and mitigation) differ by their implementation speed and easiness. As highlighted in previous chapters, some measures can be implemented rather quickly (energy efficiency measures in transport systems, installation of photovoltaic panels) but others cannot. As shown in chapters 1 and 2 (especially in Sections 1.3 and 2.4.1), many adaptation and mitigation policies rely on the development or change of urban infrastructure: buildings insulation or renovation (Sections 1.3.2, 2.4.4 and 2.2.3), public transport development (Section 1.3.3), construction of dikes (Section 2.4.3), water treatment plants and water networks (Section 2.1.3), etc. These urban buildings have generally a long lifetime, from 50 to more than 100 years, and their cost is extremely high.

The right choice of urban policies is particularly important to ensure that long-lived infrastructure — commercial and residential buildings, roads and ports, water and transport networks — is designed to withstand the expected increase in climate hazards while simultaneously improving the energy and emission performance of the built environment. Taking into account climate issues during the design and building of new infrastructure enables to prevent future retrofitting of replacement, and, hence, enables considerable long-term savings (cf. for instance Hallegatte, 2009).

Similar idea holds for the broader concept of urban forms:[1] as was studied in Hallegatte et al. (2007a); Gusdorf and Hallegatte (2007a,b); Gusdorf et al. (2008), one of

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[1] The uses of land and spatial distribution of population and activities within an urban area, as defined in Section 1.4.1.1.

the biggest challenges for cities is the tendency to lock-in the form that they grow into[2]. The consequence is that, even if urban shape is an important determinant of GHG emissions (Section 1.4.1) and flood and heatwave vulnerability (Section2.4.2 and 2.4.4), it is a difficult to act on it: structural modifications in cities occur slowly, over a long time horizon. Early action is therefore required to ensure that cities will be adapted to the climate of the end of the century and to limit their future GHG emissions. The transportation system that a city develops is of particular importance, as it largely defines the final shape of the city.

This is a critical lesson for developing-country cities that still have an opportunity to influence the final shape of their cities. Rapidly growing cities are of special concern: they will need to take urgent actions to guide building codes and practices, density, and connectivity infrastructure. In such cities, as those in China, a more compact urban form is still possible; however, the current development charges and local revenue generation do not readily encourage this (Hoornweg et al., 2011a). Delay will result in a path that will and make mitigation and adaptation increasingly expensive and inaccessible.

In many cases in urban areas, the focus is on investment in major infrastructure that lasts for a number of decades: transportation systems; commercial, residential and government buildings; and industrial development. These investments can profoundly shape both urban mitigation and adaptation not only in the short term, but for as long as half a century or more.

Taking into account inertia is therefore an important element of climate policies assessment: it must take into account both short, medium and long-term consequences. However, as highlighted in the conclusion of Chapter 1 (Section 1.5), it is difficult to anticipate long-term consequences of urban policies, because it is often hard to find a fully comparable historical example, and because it is impossible to conduct experiments for such a time scale. Modelling is a way to address this issue, and Chapter 7 will present how the different impacts of an urban climate policy (a carbon tax), can be assessed for different time-periods. It will also highlight to what extent inertia makes these impacts different from each other, and how it is possible to analyze these differences.

3.2   Uncertainties

As was already noted in previous chapters (cf. Section 1.5 and 2.5), urban policies can generally only try to influence urban shape and household choices, but cannot directly control them. For instance, transport policies can only try to influence modal share by varying transport modes price, ease of use, and efficiency, but cannot oblige people to use one specific mode. Similarly, city planners do generally not have an entire control on the future shape of their cities; planning has to compose with households aggregated choices or with market forces. Town planners and decision makers have to cooperate with operators that actually build the city (See also Lefèvre and Renard, 2011).

As explained in Giraud et al. (2010), this is especially true with the move toward deregulation and flexible planning implemented in most OECD countries and in many developing countries. Planners have essentially three types of tools : land planning, infrastructure investments and property taxes, which act indirectly. "*The real estate*

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[2]cf. also Section 1.4.1.3.

market, which reacts to the constraints and opportunities provided by regulations, in-frastructure, and taxation, will shape the city; the designs and blueprints of planners will not have much direct influence." (Giraud et al., 2010). To make cities more sustainable, reflexions about what could be an ideal city are not sufficient : the issue is rather how to redesign existing cities through anticipation, encouragement and support of "*spontaneous urban development*".

This makes using urban planning as a tool for mitigation and adaptation extremely difficult. Indeed, anticipated action is required, but the long term impacts of today's policies are not clearly known. "Spontaneous urban development" is driven by several factors on which urban decision-makers have influence (e.g. transport infrastructures, amenities such as parks, schools etc.) and factors on which they generally cannot act directly: demographic, socio-economic, cultural, political and technological changes play for instance a major role. For instance socio-economic effects of urban sprawl mitigation policies differ completely in a context of population growth or in a context of demographic decline. Their impact on climate is dependent on future transport and renewable technology production technologies, as low-density cities may enable larger decentralized renewable electricity production (cf. Section 1.4.1.1). Similarly, success of strategies aiming at reducing transport energy consumption is dependent on future transport prices. Prospective studies that explore various possible evolutions of these variables are thus an essential tool to design the best policies.

Robustness against this uncertainty should therefore be a key element in urban climate policies appraisal. In Chapter 8, we will show a first assessment of such a robustness analysis for several climate policies in Paris urban area. To achieve this, we will explain how it is possible to downscale global world evolution scenarios until 2100 (such as SRES scenarios, cf. Nakicenovic et al., 2000) at city scale, and design possible and coherent scenarios, which represent conceivable futures. The analysis of several contrasted scenarios will then enable to assess which future global evolutions appear to impact urban policies, and which do not.

3.3 Tradeoffs in climate policies

A third important issue comes from the fact that, as cities are integrated systems, all urban policies have side-effects, which sometimes may be an important obstacle or an additional incentive.

First category of side-effects, urban adaptation strategies do not always support mitigation policies: in some cases both can be complementary but in other cases they may conflict (cf. for instance McEvoy et al., 2006; Hamin and Gurran, 2009).[3] Pathways to mitigation and adaptation can be complementary and reinforce each other. For instance, building insulation, which can reduce the need for burning fossil fuels, may enable adaptation to increased temperatures and mitigate heatwave vulnerability.

But adaptation and mitigation can also conflict. Generally, the easiest way to adapt to most of climate change impacts is through an increase in energy consumption (e.g. water desalinization to reduce water resource decrease, air conditioning to reduce heat wave impacts etc.). Such a spontaneous energy intensive adaptation is in contradiction with efforts to reduce energy consumption, and, hence, GHG emissions. Anticipated adaptation may enable to prevent such a "maladaptation", and to reach an adaptation pathway compatible with low GHG emission levels.

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[3]This is generally true for adaptation and mitigation in general, but it is especially noticeable in urban areas, as urban adaptation and mitigation policies often rely on the same tools.

Using city planning as a tool for adaptation and mitigation raises such issues. For instance, strategies to limit urban sprawl to enable lifestyles that reduce per capita GHG emissions (Section 1.4.1) may increase UHI effect (Section 2.1.1), and therefore increase heatwave vulnerability (Section 2.1.1).

Another example, as explained (and empirically measured) in Burby et al., 2001 and Burby et al., 2006, comes from the fact that they may also increase vulnerability to natural disasters. Urban containment may indeed make more attractive areas that are particularly dangerous or may increase the value of land and encourage residential and commercial development in these places.[4] This will be even more true when vacant development land becomes scarce, the land situated in areas at risk may be the only land available. Since the constraints on construction, such as risks of natural disasters, are generally expressed in the price of land, dangerous land may be the cheapest land available, all other things being equal, which is another incentive to build in these places if developers are myopic (Lall and Deichmann, 2010). This problem may be countered if programs for the containment of urban spread are accompanied by complete and integrated plans to reduce vulnerability to natural disasters, but such programs are expensive, either financially or politically (cf. Section 2.4.2). These interactions will be studied in more details in Chapter 9.

If urban adaptation and mitigation policies interact, they also interact with other urban policy goals. Environmental policies can result in positive feedback with respect to economic and social issues. For instance, a decrease in car congestion increases residents' quality of life, enhances economic competitiveness, reduces accessibility inequalities among neighborhoods, and decreases air pollution and GHG emissions.

Conversely, while enlarging parks and introducing more vegetation in cities can be a useful way to adapt cities to higher temperatures and can improve the quality of life, such actions may also reduce population density and lead to increased GHG emissions from transportation. Similarly, protecting urban coastlines with dikes and seawalls decreases cities' vulnerability to floods, but can reduce recreational amenities and a city's attractiveness to tourists, thereby reducing inhabitants' incomes and slowing down development.

All policies have consequences for property values, which in turn influence the attractiveness of an urban area for potential residents, professionals, and businesses. These effects can vary by community or location, for example, impact in the suburbs versus that in the city center, leading to unintended redistributions of wealth or amenities that may or may not be consistent with policy goals.

Such conflicts among different policy goals create implementation problems, while synergies offer opportunities for win-win solutions, suggesting the utility of assessing all urban policies within a unified framework (Munasinghe, 2011).

However, in practice, such an integrated approach is not often developed. Only a few city-wide initiatives (for instance London, Durban and New York) have addressed some of the linkages between mitigation and adaptation (UN-Habitat, 2011). So far, only qualitative analysis of these interactions have been developed, and knowledge is lacking on the relative importance of these interactions, and on the effectiveness of policies aiming at counter-balancing side-effects. To achieve such a quantification,

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[4]Sydney, in Australia, can be used as an example. Urban consolidation was introduced by the Sydney Regional Plan 1970-2000 and the updates that followed, as well as by the related plans which encouraged a re-visiting of development in areas of high density. This program of consolidation and the high price of land contributed to a substantial increase in occupation of land liable to flood, occupation which government policies allowed by leaving decisions on where to allow development in these areas to local deciders. (Burby et al., 2001, 2006)

a modeling taking into account these different effects is required. One of the main issue comes from the fact that building such a framework requires aggregating results from different research fields in an interdisciplinary analysis. Moreover, because urban management implies political choices and value judgments, urban climate policies have to be judged using multiple criteria.

In Part II, we will show how it is possible to develop such a model, and we will use it to provide a first quantitative analysis of some of these interactions in Chapter 9.

3.4 Conclusion

In conclusion, to design best urban climate policies,

- anticipated action is required, and short, medium and long-term effects have to be taken into account

- the influence of various external socio-economic factors on the city is a major source of uncertainty, and makes it necessary to follow a scenario-based approach that takes into account the uncertainty on urban dynamics drivers

- beyond direct cost and effectiveness, side-effects of policies are of great importance, and their taking into account allows for more efficient and acceptable urban climate policies.

Most of these issues have been already described qualitatively or theoretically in the literature, but practical quantitative analysis is lacking. We will go in that direction in following parts.

Integrated city models (ICMs) are pertinent tools do carry out such a study (Hallegatte et al., 2010). they are highly simplified representations of reality that describe the most important drivers of city change over time and the most important interactions between various urban variables. ICMs can provide decision makers and stakeholders with useful information and can help them understand the main mechanisms and linkages at work.

Part II describes the design and calibration of such a model: NEDUM-2D, and Part III will show how it can inform on the issues we have highlighted.

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Part II

Prospective integrated city modelling

Chapter 4

Urban modelling

"Cities have always been shaped by transportation technologies."

Glaeser and Kahn (2004)

How are cities organized? What are the main factors which influence their structure? It has long been recognized that if policy action plays a definite role in shaping a city, it has to compose with the city's own evolution forces, which result from the sometimes obscure aggregation of various city stakeholders preferences (cf. Section 3.2 in Chapter 3). Urban studies have historically mostly followed a normative approach, looking at what would be an ideal city. It is not until the beginning of the XXth century that some researchers began consider city structure as a research object by itself, and not only as an imperfect state which should be corrected would the proper policy road-map be found. If social scientists were among the first to systematically inquire into cities structures, economists and transport engineers have later developed theories and analysis frameworks of great interest. Mapping all this research would be too ambitious, and we will limit ourselves here to a brief presentation of some main concepts and questions (Section 4.1), before looking at how this theory has been employed to build quantitative models which have been a help to policy-making (Section 4.2). Finally, Section 4.3 concludes and discusses to what extent a new modeling can be of interest to deal specifically with the climatic issues we have highlighted in Part I.

4.1 Theories of urban spatial organization

Following Wegener and Fürst (2004), let us divide main theories of urban organization in three broad groups : social theories (Section 4.1.1), economic theories (Section 4.1.2) and finally frameworks developed by transport engineers (Section 4.1.3).

4.1.1 Social theories[1]

4.1.1.1 The Chicago school

The first studies of time evolution of the structure of cities were made by historians, like Mumford (1938, 1961) or Gutkind (1972). However, their method was essentially

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[1]This section draws extensively on Wegener and Fürst (2004) and Lefèvre (2007).
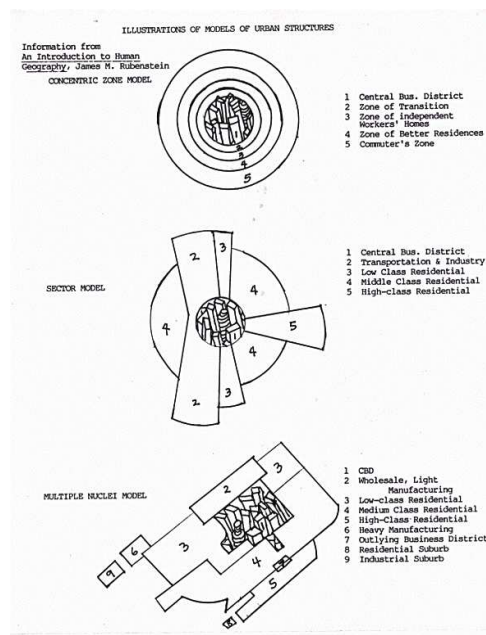
Figure 4.1: Three Models of Urban Structure. Source: Rubenstein, 1996.

hermeneutic, i.e. aimed at "*understanding individual processes as unique constellations of specific causes and effects. Beyond the observation of similarities in different places at different times, no regularities or law-like covariations of variables were sought.*" (Wegener and Fürst, 2004).

The first determinant theory for the spatial and temporal analysis of urban development was developed between the two world wars in Chicago. The Chicago school looked closely into processes of social change at the neighbourhood and urban levels. They interpreted cities as multi-species ecosystems, in which social and economic groups fight for "ecological positions", i.e. a neighbourhood or a region (Park et al., 1925; Park, 1936). Concepts of ecology such as "invasion", "succession" or "dominance" were used to describe the appropriation of space, seen as an invasion of different ethnic or income groups or tertiary activities in a residential neighbourhood.

Several qualitative theories were put forward to explain the spatial structure expansion of American cities |(Fig. 4.1), such as the concentric model (Burgess, 1925), the sector model (Hoyt, 1939), or the mutiple nuclei, or polycentric, model (Harris and Ullman, 1945). Concepts from social ecology continue to be useful for understanding the mechanisms of social change in cities beyond the economic processes on the land market, such as "gentrification" processes[2] (Smith and Williams, 1986).

4.1.1.2 Social geography theories

In the 1960's, new theories went beyond the perspective of the Chicago school models by referring to age-, gender- or social-group specific activity patterns which lead to characteristic spatio-temporal behaviour, and hence to permanent localisations. "Action-

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[2]That is the invasion of upper-middle-class households into inner-city or suburban working-class neighbourhoods.

space analyses" identified the frequency of performance of activities as a function of distance to other activities. It enabled to draw conclusions for the optimum allocation of work-places, housing, shopping and recreation facilities or the optimum level of most appropriate division of labour in cities (Wegener and Fürst, 2004).

These ideas were made operational by the introduction of "time budgets" (Hägerstrand, 1970), in which individuals, according to their social role, income and level of technology (e.g. car ownership) — subject to various types of constraints[3] — command different action spaces.

On the basis of Hägerstrand's action-space theory, Zahavi (Zahavi, 1974, 1979; Zahavi et al., 1981) proposed the hypothesis that individuals maximise activities or opportunities that can be reached within their travel time and money budgets[4]. Zahavi's theory of fixed travel budgets has been extended by the concept of flexible time and money budgets responding to external constraints (Downes, 1985). This theory allows to model also the variation in time and money budgets across socio-economic groups and different parts of an urban area and has proved to be more plausible and theoretically sound (Wegener and Fürst, 2004).

Zahavi hypothesis

Zahavi (Zahavi, 1974, 1979; Zahavi et al., 1981) studied a large number of cities all over the world and found that the time and money budgets devoted to transport vary within urban regions as a function of age, income and residential location, but that they showed a remarkable stability over time when averaged across whole urban regions. It was found that in developed countries the average time spent in travel by an active person per day is approximately 1.1 h per person per day, and the average travel expenditure accounts for about 15% of disposable household income.

His results were updated in a study by Schafer and Victor (2000): As can be seen on Fig. 4.2(a), travel time budget is stable over a wide range of income levels, geographical and cultural settings: residents of African villages devote similar time for travel as those of Japan, Singapore, Western Europe or North America. Figure 4.2(b) shows that similar conclusion holds, to a lesser extent, for proportion of income devoted to traveling.
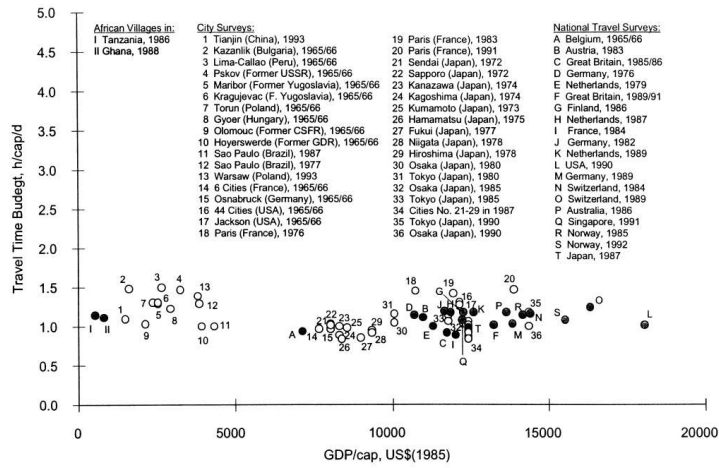
This temporal stability of time and money budgets for transport explain why in the past gains in travel speed have generally rather been used for more and longer trips than for time savings. It therefore explains that over the last forty years transport prices decrease in most developed countries has not led to a reduction in travel expenditure and time, but has led more and more people to chose residential locations on the far periphery of urbanized areas.
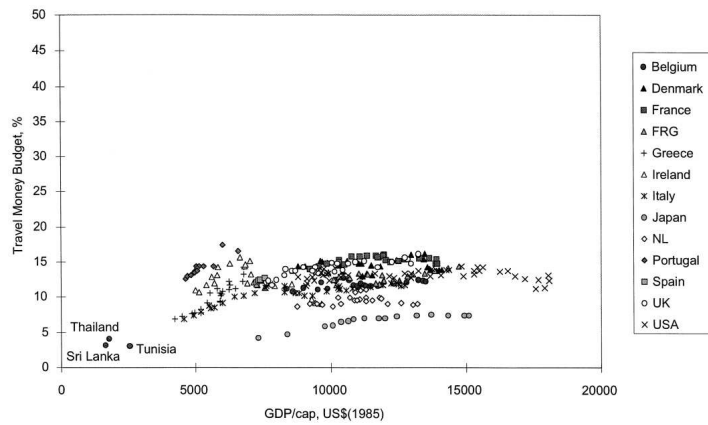

4.1.2 Economic theories

In the 1950's the role of transport on the spatial development of cities began to be regarded as essential (cf. Clark, 1958), and "*the recognition that trip and location decisions co-determine each other and that therefore transport and land-use planning needed to be coordinated, quickly spread among American planners*" (Wegener and

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[3]There are three types of constraints : capacity constraints (personal, non-spatial restrictions on mobility, such as monetary budget, time budget, availability of transport modes and ability to use them), coupling constraints (restrictions on the coupling of activities by location and time schedules of facilities and other individual) and institutional constraints (restrictions of access to facilities by public or private regulations such as property, opening hours, entrance fees or prices). (Wegener and Fürst, 2004)

[4]Instead of minimizing travel time or travel cost needed to perform a given set of activities, as the conventional theory of travel behaviour assumes.

Figure (a) — Travel Time Budget, h/cap/d vs GDP/cap, US$(1985)

African Villages in:
I Tanzania, 1986
II Ghana, 1988

City Surveys:
1 Tianjin (China), 1993
2 Kazanlik (Bulgaria), 1965/66
3 Lima-Callao (Peru), 1965/66
4 Pskov (Former USSR), 1965/66
5 Maribor (Former Yugoslavia), 1965/66
6 Kragujevac (F. Yugoslavia), 1965/66
7 Torun (Poland), 1965/66
8 Gyoer (Hungary), 1965/66
9 Olomouc (Former CSFR), 1965/66
10 Hoyerswerde (Former GDR), 1965/66
11 Sao Paulo (Brazil), 1987
12 Sao Paulo (Brazil), 1977
13 Warsaw (Poland), 1993
14 6 Cities (France), 1965/66
15 Osnabruck (Germany), 1965/66
16 44 Cities (USA), 1965/66
17 Jackson (USA), 1965/66
18 Paris (France), 1976

19 Paris (France), 1983
20 Paris (France), 1991
21 Sendai (Japan), 1972
22 Sapporo (Japan), 1972
23 Kanazawa (Japan), 1974
24 Kagoshima (Japan), 1974
25 Kumamoto (Japan), 1973
26 Hamamatsu (Japan), 1975
27 Fukui (Japan), 1977
28 Niigata (Japan), 1978
29 Hiroshima (Japan), 1978
30 Osaka (Japan), 1980
31 Tokyo (Japan), 1980
32 Osaka (Japan), 1985
33 Tokyo (Japan), 1985
34 Cities No. 21-29 in 1987
35 Tokyo (Japan), 1990
36 Osaka (Japan), 1990

National Travel Surveys:
A Belgium, 1965/66
B Austria, 1983
C Great Britain, 1985/86
D Germany, 1976
E Netherlands, 1979
F Great Britain, 1989/91
G Finland, 1986
H Netherlands, 1987
I France, 1984
J Germany, 1982
K Netherlands, 1989
L USA, 1990
M Germany, 1989
N Switzerland, 1984
O Switzerland, 1989
P Australia, 1986
Q Singapore, 1991
R Norway, 1985
S Norway, 1992
T Japan, 1987

(a) Average per-capita travel time budget from African villages, 44 city and 20 national surveys.

Figure (b) — Travel Money Budget, % vs GDP/cap, US$(1985)

Legend:
• Belgium
▲ Denmark
■ France
△ FRG
+ Greece
△ Ireland
× Italy
⊙ Japan
◇ NL
◆ Portugal
▣ Spain
○ UK
× USA

Thailand
Sri Lanka • Tunisia

(b) Travel money budget in 13 industrialized countries, 1970 to 1992. Also shown are data from household expenditure surveys in three developing countries.

Figure 4.2: Time and money budgets devoted to transport vary within urban regions as a function of age, income and residential location, but that show a remarkable stability. Source: Schafer and Victor, 2000.

Fürst, 2004). For instance,Hansen (1959) demonstrated that, in Washington, DC, locations with good accessibility had a higher chance of being developed, and at a higher density, than remote locations.

Economic theories of city organization are based on the idea that locations with good accessibility are more attractive and have a higher market value than peripheral locations. This fundamental assumption goes back to Von Thünen (1826) and has since been varied and refined in many ways (Wegener and Fürst, 2004). The most influential model is probably the urban land market model by Alonso (1964), and its developments by Mills (1967) and Muth (1969). It aims at explaining the spatial distribution - across the city - of the costs of land and of real estate, housing surface, population density and buildings heights and density. It is based on two main mechanisms.

First, households choose their accommodation location and size by making a trade-off between the proximity to the city center (i.e. to the jobs) and the real estate price level (or, equivalently, between the proximity to the city center and the housing surface they can afford).

Second, land owners choose to build more or less housing (i.e. larger or smaller building) at a specific location, depending on the local level of real estate prices. When these prices are low, developers tend to build low density buildings, and when these prices are high, they tend to build high density buildings.

Using these two mechanisms, it is possible to determine the structure of the city from information on the population size, the households' income, transport network locations, building construction costs and developers behavior parameters. An immediate consequence of this model is for example the fact that, if the price of transportation increases, households will have less incentive to live in the suburbs and the city density will increase close to the center. A more detailed description of this model and of its main properties is in the following box. One of the main success of this model is its ability to explain the regular broad exponentially decrease in population density empirically observed in several cities across the world (cf. the original study by Clark (1951) or Bertaud (2002) for updated figures).

Several developments have been made to this model (see for instance Fujita, 1989 for a review). One first direction aimed at taking into account the possibility of multiple interest centers in the city : multiple location of jobs across the city (cf below), or "amenities" (security vs. insecurity, good schools, parks, beaches, public infrastructures etc.) either exogenous or endogenous (e.g. negative amenities linked to pollution, or positive amenities linked to low population densities (see for instance Papageorgiou, 1973).

Another direction looked at better descriptions of transport systems (e.g. endogenous congestion) or of building construction (cf. Masson, 2000a for a review). Finally, a last direction aimed to take into account the coexistence of several types of households with different behaviors (cf. among many other, Brueckner et al., 1999). These studies allowed to improve to some extent the model coherence with population and real estate variations empirically observed in cities, beyond the broad exponential decrease when one moves away from city center (Richardson, 1977).

4.1.3 Transport engineers frameworks

Simultaneously to urban economic theory development, several operational models of
land-use transport interaction were developed to inform policy-making. These models
also used transport as a main factor explaining cities shapes, but were developed after
observed regularities of certain parameters of human mobility and city development,
with no theoretically founded explanation for the spatial behavior. For instance, the first
determinant model of this sort, Lowry's (1964) Model Metropolis was based on famous
observations by Ravenstein (1885) and Zipf (1949) that, in an obvious analogy to the
law of gravitation in physics, the frequency of human interactions such as messages,
trips or migrations between two locations (cities or regions) is proportional to their size,
but inversely proportional to their distance (Wegener and Fürst, 2004). This enabled
to define a global attractivity associated to each location, which determined population
density through an ad-hoc function.

Contrary to contemporary urban economic models, these models were able to de-
scribe cities with multiple job locations instead of a unique city center, and the em-
pirically good results of this type of modeling led to efforts to provide a theoretical
foundation. Formulations derived from statistical mechanics (Wilson, 1967) or infor-
mation theory (Snickars and Weibull, 1976), both of which led to functional forms
close to gravity models, were therefore designed. However, they still did not provide
any explanation for the spatial behavior (Wegener and Fürst, 2004). Such an expla-
nation finally came through Anas (1983), which proved the mathematical equivalence
between such models and random utility theory (McFadden, 1978), itself related to

psychological models of human decision behaviour (Luce, 1959).

4.2 A brief review of urban evolution prospective modeling

Since the middle of the XXth century, several numerical models have been designed to forecast urban development, and inform policy-making. These models are based on very different mechanisms, which are sometimes directly derived from the theoretical results presented above, and sometimes based on similar ideas but with several simplifications. Extensive reviews of land use change models exist, and we will only present here a brief overview (see for example Pagliara and Wilson, 2010; Haase and Schwarz, 2009; Verburg et al., 2004). [5]

Models can be broadly divided in two groups : geographic models, based on an extrapolation of past tendencies (Section 4.2.1), and land-use transport interaction (LUTI) models (Section 4.2.2).

4.2.1 Geographic models

Geographic models are based on the extrapolation of past tendencies: they study past evolution of a city to anticipate its future. There are several ways to do it, characterized by their higher or smaller complexity. This kind of method has been being widely used since the 1980s when access to satellite images became relatively easy. Various methods and algorithms enable to detect and analyze land-use in terms of its nature, its extension and its spatial structure. Impermeable surface detection is often used as an indicator of urban sprawl (Epstein et al., 2002), to represent build surfaces, transport axes, industrialized spaces etc. Models can rely on statistical regressions (see for instance Jat et al., 2008), Markov chains or cellular automata (see for instance Solecki and Oliveri, 2004).

This approach allows for precise and rich projections. It enables to take into account urban development in its diversity. However, it is only valid over the short-term. Indeed, as a simple extrapolation from the past, it does not take into account the changes in the factors explaining these variations. For instance, these models cannot analyze consequences of an abrupt change in oil prices. Such models also cannot assess the consequences of non-urban planning policies, such as a carbon tax, on the city structure. They are therefore not suited to address the issues raised in Chapter 3.

4.2.2 Land-use transport interaction models

A second set of methods proposes to model main evolution drivers, especially land-use transport interaction (see Iacono et al., 2008, for a review) : it tries to understand the logic of main past evolutions. Relating these variations to external changes enable to deduce their future foreseeable consequences. In such a method, only a small number of factors have to be chosen: the ones which seem to have the biggest influence on urban form. Then, this influence has to be studied and modeled. To do a scenario, the impact of the evolution of these factors is computed, supposing everything else remains constant. The main disadvantage of this method is that many phenomena are

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[5]Older reviews include Batty, 1976; Bertuglia, 1987; De la Barra, 1989; Batty, 1994; Wegener, 1994; Verburg et al., 2004; Wegener, 2004...

neglected : the outcome is only an approximation of reality. The main advantage is that the simulations are easily understandable, as is the influence of each parameter, and that these models are based on mechanisms that are supposed to remain valid in the future, while past-trends extrapolation is always questionable.

Most models of this type take transport as the main determinant of city structure. As explained in Section 4.1.3, the first determinant model of this kind, Lowry's (1964) Model Metropolis, was linking a measure of transport accessibility to population density. This model stimulated a large number of increasingly complex modelling approaches such as the work by Goldner (1971), Geraldes et al. (1978), Putman (1983, 1991), Mackett (1983) and Webster et al. (1988). Boyce et al. (1981) developed combined equilibrium models of residential location, mode and route choice.

However, these models assumed equilibrium between transport and location, whereas urban processes have very different speeds and response times. For instance, although activity location and households houses evolve slowly, behavior of transport users adjusts quickly to changing conditions in the transport system. Secondly, these models also lacked economic content, which made the model incapable of considering wider choices than between transport modes or destinations (for instance choices involving trade-offs between transport and location or between housing and work-place location).

After Anas's work (Anas, 1983), non-equilibrium models including urban economic based mechanisms were produced, among which MEPLAN (Echenique and Williams, 1980), TRANUS (De la Barra, 1982), METROSIM (Anas, 1982), IRPUD (Wegener, 1982), URBANSIM (Waddell et al., 2003) etc. A main difference between them lay in the level of complexity and details.

To deal with issues raised in Chapter 3, these last models appear more appropriate than geographic models, as they enable to do projections to the longer term, and to assess the impact of more policies and events (e.g. changes in oil prices or transport technologies). They are and have been used in some research projects to assess urban climate policies (for instance in Bangalore Lefèvre (2009) and Grenoble Criqui et al. (2010)).

However, another drawback prevents us from directly using such models here. These models, even the most simple ones, are indeed extremely complex. They all take into account a great number of mechanisms and require detailed data to be calibrated. The question of models optimal complexity is difficult. If an increased complexity leads to a more detailed depiction of reality, it also leads to a loss of comprehension of the processes involved and of the results robustness (the "black box" problem). Secondly, the higher the complexity, the more important is calibration on present day urban area, and the more constrained is model evolution dynamic. Indeed, all the parameters which have to be set to describe as exactly as possible present-day city constrain the simulation. Most detailed models can do very good projections of city evolution over ten or twenty years, but are not designed to do long-term projections, or to study deep changes in a city structure[6].

4.3   Conclusion : optimal model complexity

Models can be used to answer different questions, at different steps in the decision-making process. They can be helpful to design broad strategies, or to design finer scale policies. When the aim is to frame a broad strategy under the context of uncertain fu-

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[6]Another advantage is that simpler models are easier and quicker to calibrate, and require less data.

tures, as is the case with climate issues, simple models can be of greater interest than more complex ones. As said in Hardy (2012), there is "*an unmet need for a simplified modeling tool that could be used to support transportation and land use policy assessment. [...] Model development should not focus on more complex computer modeling tools that may accurately predict the future (which significant evidence shows they cannot), but less complex tools that can assist decision makers in knowing which data elements cause the most uncertainty to enable more robust decision making.*" This is what we propose to do.

Between urban economic theory models, which describe theoretical cities (equilibrium, simple transport network, optimal investments...) and high-complexity models, there is a gap which has not been filled. We need here a model, simple enough to remain tractable and based on general and fundamental economic principles, but without the most unrealistic assumptions of theoretical models (equilibrium, optimality of investments, perfect foresight and rationality, simplified representation of urban space and transport system), so that it can describe quantitatively actual cities, following the work began by Gusdorf (2008).

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Chapter 5

A first static model

In this chapter, we present a simple modeling of household location, of urban area size and of real estate prices. It is based on the urban economics framework, which has been described in Section 4.1.2 in Chapter 4. Urban economics standard model has been modified and interpreted to be able to quantitatively describe average behavior of households and developers (Section 5.1). As a case study, we present here a calibration of this model on Paris urban area[1], using a broad range of detailed socio-economic data (Section 5.2 presents the data and Section 5.3 the calibration process). We find that the model reproduces fairly faithfully the available data on the Paris area (5.4), suggesting that this tool can be used to inform policy decisions. A rigorous validation is however only possible by calibrating the model on several cities with different characteristics. As a first step, calibration of the model on London and on other French cities is also presented in Sections 5.5 and 5.6.

5.1 Principle of the model

5.1.1 Equations

We model the household trade-off using the following utility function :

$$U(r) = Z(r)^{\alpha} h(r)^{\beta} \tag{5.1}$$

where r is the location in the city, α and β are coefficients ($\alpha + \beta = 1$), $q(r)$ the surface of the households' dwelling and $Z(r)$ the money remaining after the household has paid its rent and a commuting round-trip per day to the center of Paris. The cost of transportation includes the monetary cost of transportation and the cost associated with the trip duration[2]. Such a functional form is consistent with the fact that the share of household income devoted to housing expenditures is relatively constant over time and space (Davis and Ortalo-Magne, 2010). Households' income constraint reads :

$$Y = Z(r) + q(r).R(r) + T(r) \tag{5.2}$$

where Y is household income and is constant ($\forall r, Y(r) = Y$), R is the rent per square meter, and $T(r)$ transportation costs (monetary cost added with time cost).

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[1]A modeling of Paris urban area using such a framework but different data and assumptions has been proposed by Rouchaud and Sauvant, 2004.

[2]We consider the cost associated with the trip duration as an actual loss of income

We assume that absentee landowners own the land, and that they combine land $L'(r)$ with capital $K'(r)$ to produce housing $H'(r)$. The housing production function reads, in a classical way (Muth, 1969; Thorsnes, 1997) :

$$H'(r) = AL'(r)^a K'(r)^b \tag{5.3}$$

where A, a and b are coefficients ($a + b = 1$), $H'(r)$ the housing surface built, $L'(r)$ the ground surface occupied by the buildings and $K'(r)$ the financial capital used for construction. The benefit of land owners reads therefore :

$$\Pi = (R - R_0)H'(r) - (\delta + \rho)K'(r) \tag{5.4}$$

Π is the profit, ρ represents the joined effect of real estate capital depreciation and annual taxes payed by land owners on the real estate capital, and δ the interest rate. Developers build to maximize their profit : at each point of the metropolitan area they construct, i.e. choose $K'(r)$, to maximize $\Pi(r)$ under the constraint that $\frac{H'(r)}{L'(r)}$ ratio is limited by an urbanism constraint (see details below). The metropolitan area boundary is defined by a rent R_0, below which it is not profitable to build housing building (this value corresponds both to other use of the land like agriculture and to transaction costs in the building and renting process).

As for the other equations that we have presented, let us reason per unit of land : because $a + b = 1$, we get :

$$\frac{H'(r)}{L'(r)} = A \left(\frac{K'(r)}{L'(r)} \right)^b \tag{5.5}$$

So if we define $H(r) = \frac{H'(r)}{L'(r)}$ and $K(r) = \frac{K'(r)}{L'(r)}$, we have :

$$H(r) = A(K(r))^b \tag{5.6}$$

5.1.2 Hypotheses of the model

5.1.2.1 Monocentric city

We suppose that there exist a unique city center. If, rigorously speaking, recent trends in Paris urban area development seem to contradict this assumption, it is still reasonable to accept it, at least in first approximation, as can be seen in as can be seen in Fig. 5.1 : rents and population density reach a peak at a point that corresponds to the center of Paris and decrease in all directions on a regular basis when one moves away. High job density near the center of Paris and Paris urban area star-shaped public transport network also contribute to the relevance of the monocentric approach.

For a question of simplicity and clarity, we have therefore put aside the issue of polycentrism, to develop only scenarios in which urban area keep evolving in a mono-centric way.[3] Results presented below confirm that the monocentric assumption is still able to explain the major characteristics of the Paris urban area. We come back to this question in the conclusion of this document.

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[3]Polycentrism could be modelled by using slightly more complex equations and random utilities, cf. for instance Anas and Kim, 1996.
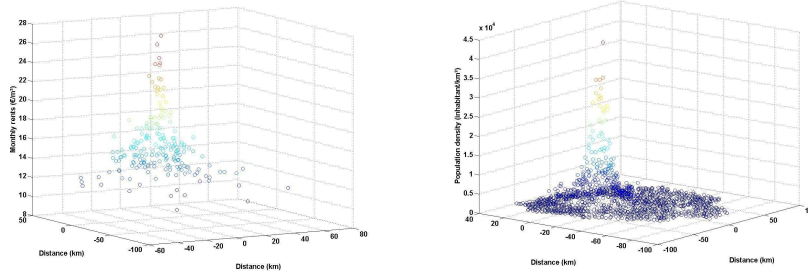
(a) Rents in Paris administrative region (Ile-de-France) (source : Clameur).

(b) Population density in Paris administrative region (Ile-de-France) (source : INSEE).

FIGURE 5.1 – Rents and population density in Paris administrative region (Ile-de-France).

5.1.2.2 Market mechanisms

Second, this model only describes market mechanisms related to urbanism. In practice, because of urbanism constraints (e.g. limits to building heights) and of direct public investment (e.g. in public housing or infrastructure) the structure of the Paris urban area does not directly correspond to the resulting balance of the free play of market. We introduce explicitly constraints of this type in the model. For instance, we limit the height of buildings in Paris. Indeed the model tells us that, otherwise, real estate developers would build much higher buildings than what is observed, in response to the high rent level in Paris. We also forbid to build in some areas (natural parks, public gardens...). In the policy analyses, we introduce additional land-use regulations (cf. Chapter 8 and 9).

We do not describe direct public investment aiming at changing the urban shape. For instance, "Villes nouvelles" ("new towns")[4] are an historic example of a planned urban development that the model is not able to anticipate, and which could renew itself in this century. Thus, it can be considered that the model provides spontaneous urbanization trends, that urban policy course may alter.

We also exclude social housing from our field of study, because it is strongly regulated and do not follow free market forces. Since the access to social housing is constrained in practice[5], we assume that the existence of social housing has a limited influence on the private market. More precisely, this means that we assume that households cannot make social housing and private housing compete, which would result in a reduction of private real estate prices until they become comparable to social housing prices.

5.1.2.3 One household type

Given the level of abstraction and the exploratory nature of this work, we have here neglected the influence of local distribution of household income. One obvious development is the introduction of the heterogeneity of households (including income

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[4]These new towns were created from scratch in France in the mid-1960s to try to control the expansion of several cities. For example Cergy-Pontoise, Marne-la-Vallée, Sénart, Évry and Saint-Quentin-en-Yvelines were created around Paris.

[5]In 2007, for instance, only about 7% of demand for social housing in Île de France was fulfilled (OLS, 2008).
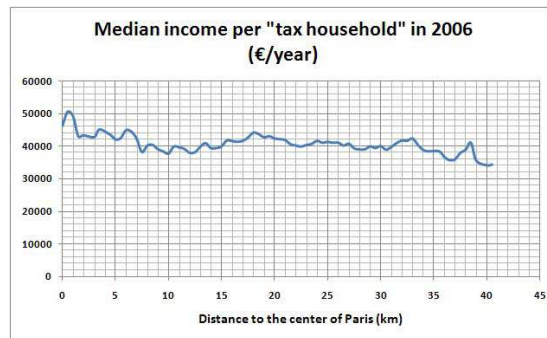
FIGURE 5.2 – Average income per "tax household" (Source : INSEE).

differences) in the analysis. As can be seen in Fig. 5.2, excluding the center of Paris, average income[6] per "tax household"[7] as a function of the distance to the center of Paris varies less than 16 % in the first 30 km. Hence this simplification seems reasonable, at least as a first order approximation. We come back to this question in the conclusion of this document.

5.2 Data

5.2.1 Land-use

Computations are done on a 100×100km grid, with square 1km cells. Each cell is made up of free and restricted land, each of which use a fraction of the grid area. Restricted land is land where house building is forbidden, such as forests, parks, rivers, lakes, airports etc. Free land is land where building is authorized[8]. A detailed explanation of data used to determine restricted land and free land can be found in Appendix 5.A.

In a city, the ground surface is not only devoted to housing, but also to transportation infrastructures : roads, sidewalks, railways, etc. The surface devoted to these infrastructures is far from negligible, so we had to take them into account and to introduce a constraint on the maximum ground surface devoted to housing construction. We based our constraint on data gathered by the Paris urbanism institute (APUR) for the EPICEA research project. According to pictures taken by airplane, roofs cover 62% of ground surface in most dense areas in Paris, public parks excluded ; we therefore suppose that, in free land, only 62% of ground surface is available for building.

5.2.2 Demographic data and urban structure

There are different definitions of what is commonly known as an "urban area." Here we use the definition corresponding to the concept of "aire urbaine " as defined by

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[6]Data are provided by INSEE (French National Institute for Statistics and Economic Studies), and are available online at http://www.insee.fr/en/methodes/default.asp?page=definitions/unite-consommation.htm

[7]"tax household" refers to all the people included on the same income tax declaration. About the exact definition see http://www.insee.fr/en/methodes/default.asp?pageefinitions/foyer-fiscal.htm.

[8]But its height might be limited by land use planning constraint, cf. Section 5.1.2.2.
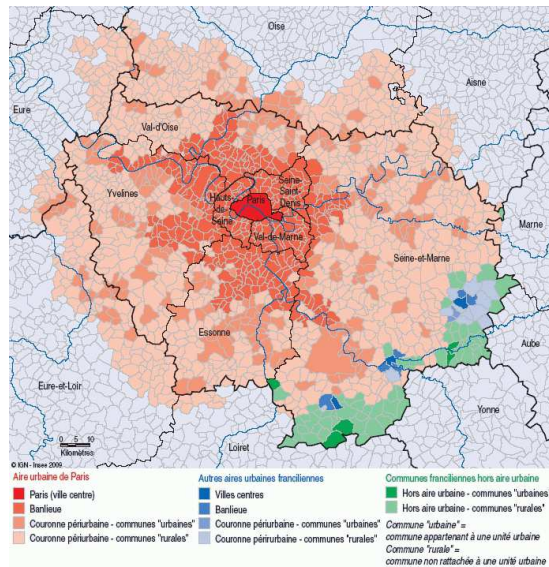
FIGURE 5.3 – Map of Paris urban area. Source : INSEE, IGN.

INSEE ("aire urbaine" literally translates as urban area, so we will use these two wordings interchangeably) : "An urban area is a group of municipalities, all adjoining and without enclaves, made up of an urban hub and rural municipalities or urban units (suburban rim), of which at least 40% of the resident working population works in the hub or in municipalities attracted by the hub." The "aire urbaine" definition is close to the concept of urban area as described by our model. Indeed, a location belongs to our model urban area if localization choices of its inhabitants are primarily driven by proximity to Paris center.

The urban area of Paris does not exactly match geographically Paris administrative Region ("Ile-de-France") (Fig. 5.3). However, in 2001, 97 % of Paris "aire urbaine" inhabitants live in Ile-de-France and 99 % of the population of Ile-de-France lives in Paris "aire urbaine" (Hassan, 2001). When we do not have data specific to Paris "aire urbaine", therefore, we use data describing Ile-de-France.

In terms of demographic data, we use the sum of the populations of Paris urban area municipalities, 11 768 725 inhabitants, established by INSEE through the national population census for the year 2006. We also used the average size of households in 2005 for Paris urban area[9] , namely 2.3 people per household. The median disposable income of households[10] was determined by INSEE for the region Ile-de-France in 2006[11] , and is equal to 56,098 € per year per household.

There are several databases listing rent levels in Ile-de-France. In our study, we used the database provided by CLAMEUR[12] , an association of several public and private organizations that studies the evolution of rents in France. This database includes

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[9]http://www.insee.fr/fr/themes/document.asp?ref_id=12006&page=alapage/alap292/alap292_graph.htm

[10]Income resulting from the distribution of added value, the distribution of income from property and redistribution operations.

[11]http://www.insee.fr/fr/themes/tableau.asp?reg_id=99&ref_id=CMRSOS04238

[12]http://www.clameur.fr/lmecv_regvil.htm

observed rents (excluding social housing) for many districts in Ile-de-France.

For dwelling size, we used data collected by INSEE[13] on the size of households' main homes in Paris and its suburbs in 2006. Unfortunately, these data were limited : we do not have the complete description of the spatial repartition of dwelling sizes in the agglomeration but only an average for Paris, an average for near suburbs and an average for the whole Ile-de-France. This limitation had implications in our model calibration (section 5.4.2).

5.2.3 Interest and depreciation rates

An accurate value for interest rate is not very important in our study. Indeed, it only affects construction costs obtained during the calibration of the model, and it is difficult to verify the compatibility of these costs with reality (cf. section 5.3.2). We therefore use a reasonable approximation of interest rates of 5 %.

It is difficult to assess the depreciation rate of Paris buildings. According to the 2008 Observatory of co-ownership expenses[14] , co-ownership expenses which are devoted to local taxes and maintenance of the building were about 7.3 €/m^2/year in 2008, with exceptional burden of the order of 3.6 €/m^2/year, which were to be paid exceptionally for some years[15] . Taking an average construction cost of 1400 €/m^2 (cf. Section 5.3.2), this corresponds to between 0.8 % and 0.5 % of the original construction price of the building, depending on the frequency of these exceptional loads, i.e. a depreciation time ranging from 130 years to 190 years. The costs associated with depreciation of built capital are very low compared to financing costs due to interest rate, so a choice of a 0.8 % or 0.5 % rate has in practice no influence on the results of our model (which we can also see retrospectively in the sensitivity analysis that we conduct in Section 5.4.3). In the following, a rate $\rho = 0.5\%$ is used.

5.2.4 Transport

In terms of transportation costs and trip duration, we relied on a study by D. Rouchaud and A. Sauvant (Rouchaud and Sauvant, 2004). They have built a database of transport times to reach the center of Paris from different municipalities of Ile-de-France, by public and individual transport during morning and evening peak hours.

We used for the year 2008 a fuel cost of 1.1 euro per liter, and fuel consumption for individual cars of 7 liters for 100 km. We only deal here with perceived travel cost, and not with real travel cost, so we only use the cost of fuel and do not add costs due to vehicle amortization (we followed the same approach as Coulombel, 2010). Public transport costs were estimated based on monthly public transportation system passes prices in 2008.

5.3 Calibration

Table 5.1 presents the numerical data we used in our simulations. In absence of adequate data for some parameters, for instance the cost of time and construction costs,

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[13]http://www.insee.fr/en/themes/document.asp?reg_id=20&ref_id=13321&page=alapage/alap301/alap301_graph.htm

[14]http://www.unis-immo.fr/actualites-immobilieres.htm?lang=fr&idtexte=1168

[15]72% of Paris urban area main accommodations are collective accommodation in 2006, according to the 2006 Census population of INSEE

these parameters have been calibrated on the Paris structure in 2008 (Tab. 5.2). A detailed comparison of model results with available data is provided below, and shows a good agreement on the model with observed urban evolutions.

Input data	Value
Urban area population	5,101,300 households
Fraction of ground surface devoted to housing	0.62
Households average income	56,098 €
Transport times and costs in Paris urban area	cf. Section 5.2
Interest rate	$\delta = 5\%$
Built capital depreciation time	$\rho = 0.5\%$

TABLE 5.1 – Summary of input data

Calibrated parameters	Value
Households utility function parameter (cf. Section 5.1.1)	$\alpha = 0.7$
Coefficients of construction cost function (cf. Section 5.1.1)	$A = 2.0140$ and $a = 0.36$
Cost associated with travel time	cf. Section 5.3.3
Rent determining city border	$R_0 = 11 \, €/m^2$
Maximum floor-area ratio	1.5 (cf. Section 5.3.1)

TABLE 5.2 – Summary of calibration parameters

5.3.1 Maximum floor-area ratio in the center of Paris

Data lead to 1.5 as the value of the maximum floor-area ratio in the center of Paris. This value may seem low as most buildings in Paris have approximately 6 floors, which would induce a ratio of about 6 at the center of Paris. However, our ratio is only taking into account housing surface, and not the total built surface, and the discrepancy is simply caused by built surface intended for purposes other than housing (it includes, on the one hand, corridors and lobbies in buildings dedicated to housing and, on the other hand, all buildings not dedicated to housing : offices, shops, museums, train stations, office buildings, schools, universities, etc.).

5.3.2 Construction costs

The calibration process provides construction costs between 1173 €/m^2 for a housing-surface/land-surface ratio of 2 and 794 €/m^2 for a ratio of 1. We compare in Fig. 5.4 the calibrated costs to construction cost estimates from the Centre Scientifique et Technique du Bâtiment (CSTB), a French public institution providing analysis and research on construction and housing issues. These data are partial, since they are prices announced by developers in several public procurement documents and in various estimates of building construction costs, as well as technical documents. What emerges from CSTB data is an average cost of construction of 1200 €/m^2 before tax, or approximately 1400 €/m^2 including all taxes, which increases slightly as the building becomes
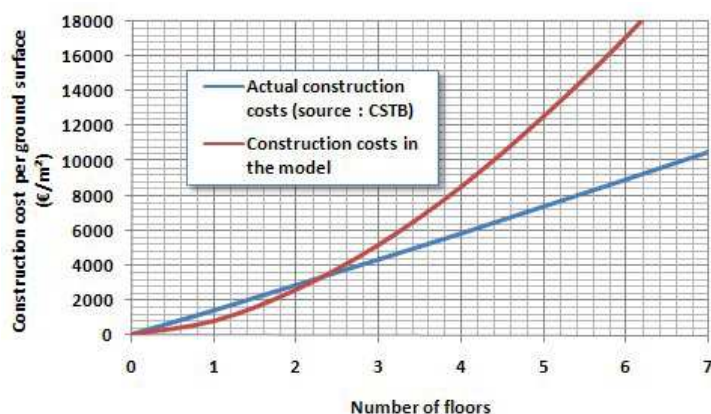
FIGURE 5.4 – Construction costs

higher. However, these estimates are quite uncertain : because of the diversity of types of buildings that it is possible to build, it is difficult to obtain a cost that can be used as a reference cost. The order of magnitude of the calibrated cost seems to agree with the order of magnitude of the data.

These data present however a less convex profile than calibrated data. An explanation of the discrepancy may be that the so-called "actual" costs in CSTB data are direct construction costs, while in reality developers consider also additional costs when the height of buildings increases (Castel, 2007). These additional costs include administrative costs (building permits etc.), financial costs (the risk associated with a larger investment cost), and technical costs (duration and technical difficulty of the works), which may introduce more convexity in the real cost curve. Another complementary explanation if a preference for detached housing, which would transcribe in our calibration as a lower cost for low-density buildings construction.

5.3.3   Cost of time

In the model, rents (per surface unit) decrease when moving away from the center of Paris because households have to pay a generalized transportation cost, which is the sum of a perceived monetary cost (interpreted here as the cost of fuel) and of the cost associated with transport time, assuming that households do a round-trip per day towards the center of Paris. In the simulation, cost associated with transport time represents generally the bigger part of generalized cost, and the way we assess this cost has an important role in our results.

Numerous studies have dealt with this issue, but no conclusive result exists on this complex subject. In Ile-de-France, French Government's Strategic Analysis Center proposed to use net hourly wage as an estimate for commuting time cost, but explained that the value of actual commuting time cost depends greatly on several factors such as households characteristics or modal choice (Boiteux and Baumstark, 2001).

Due to the importance of time cost choice in the simulation, we calibrated time cost instead of using an a priori fixed value. We computed this cost using our data on rent spatial distribution : out of these data, assuming our model perfectly exact, it is indeed possible to estimate a theoretical generalized transportation cost. Assuming that this generalized cost reflects the sum of the direct cost of transport and of the
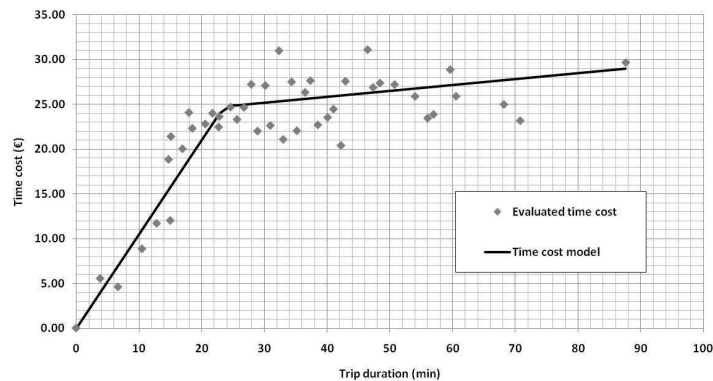
FIGURE 5.5 – Transport time cost as a function of journey time.

cost associated with transport time, and assuming that households do a round-trip per day towards the center of Paris, the transport time cost was estimated as a function of journey time.

Marginal time cost seems to decrease with travel time, and we chose to model simply this decrease using a piecewise affine function. This representation leads us to use a cost time worth 105% of the net hourly wage when the travel time is less than 25 min (or, equivalently, when the distance to the center of Paris is less than 15 km), then a very low cost (6.6% of the net hourly wage) for portions of journey in excess of this limit. The value of time for journeys during less than 25 min is therefore very close to commuting time cost in Ile-de-France according to French Government's Strategic Analysis Center.

This observed decrease in marginal time cost can be attributed to the limits of our approach, in particular to the monocentric framework and to the hypothesis that households do a round-trip per day towards the center of Paris. In the real world, in places where travel time exceeds 25 minutes, a large fraction of households do not commute to the center of Paris. This leads to a shorter average trip length than in the mono-centric case, and using actual average trip length would enable to use more realistic time cost values and smaller total fuel costs for locations far from Paris city center. In absence of needed data, we did not take into account explicitly this variation in trip length, and modeled it with a non-linear time cost.

5.4 Analysis of the simulations

5.4.1 Urbanized surface

As can be seen on Sup. Fig. 5.6, the model reproduces well Paris urban area general shape. The main mismatch is in the north of Paris, near Charles-De-Gaulle airport : in model simulations, this area is urbanized, whereas in reality it is not. This can be partly explained by the airport noise zone, which limits city expansion, and which is not taken into account by the model. The same phenomenon can be observed near Orly airport, in the south of the urban area. Conversely, in the west (Mantes la Jolie) and in the south of the urban area (Melun), the model does not capture observed urbanized areas. These two zones correspond to cities which were built long before being included in
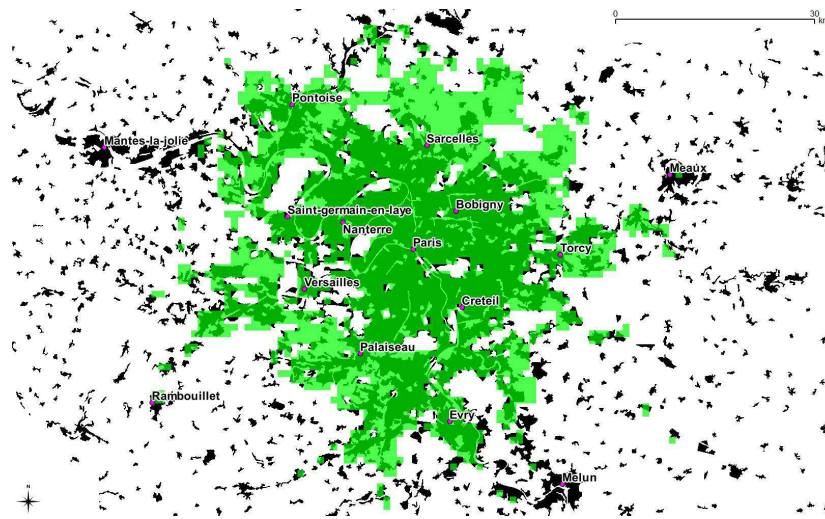
FIGURE 5.6 – Simulated urbanized area in 2006. Actual urban area appears in black (Source: Corinne Land Cover), whereas model simulation appears in transparent green.

Paris urban area, whereas the model only represents built areas due to Paris urban area sprawl.

5.4.2 City structure

As shown in Fig. 5.7(a), the model describes the distribution of rents across the city in 2008 quite satisfactorily. In two dimensions, the model explains 51.8% of the variance in rents. When all areas at a given distance from the center are averaged, the model explains 89.5% of the uni-dimensional variance. Indeed, doing so cancels out other characteristics of the area (e.g., amenities, quality of public services), and the proximity from city center is the major driver of housing prices. Figures 5.9 shows the comparison between model results and rent data on a map. A broad pattern emerges : the model appears to under-evaluate rents in rich districts, and to over-evaluate them in poor districts : introducing several household classes would enable to investigate more into this discrepancy.

Figure 5.7(b) shows that there is also a good agreement between the model and data in terms of population density. The model explains 77.2% of the two-dimensional variance in population density, and 95.9% of the uni-dimensional variance. Fig. 5.10 shows these comparisons on a map : the model appears to over-evaluate population density far from public transport axes, until a certain distance after which it under-evaluates it. This may be a limitation due to the monocentric assumption : there are people everywhere over the territory, even outside Paris urban area, whereas the model only simulates population strongly linked to Paris city center.

Similarly, Fig. 5.8(a) shows a reasonable agreement in terms of dwelling size, even though we have little data on this aspect and the curve representing "interpolation of INSEE data" should be considered carefully.

Figure 5.8(b) compares the ratio between inhabited surface and ground surface dedicated to housing as calculated by our model and as computed from our data on population density and on accommodation sizes. The curve representing model results grows when moving towards the center of Paris, and saturates at a ratio of 2, driven by

land-use constraints in Paris downtown. This value may seem low as most buildings in Paris have approximately 6 floors, which would induce a ratio of about 6 at the center of Paris. However, our ratio is only taking into account housing surface, and not the total built surface, and the discrepancy is simply caused by built surface intended for purposes other than housing (it includes, on the one hand, corridors and lobbies in buildings dedicated to housing and, on the other hand, all buildings not dedicated to housing : offices, shops, museums, train stations, office buildings, schools, universities, etc.). As we had little data on accommodation sizes, the data points should be considered more as orders of magnitude than as a specific value.

Model and data seem to match well on the urban area scale, even if local differences can be large, due to the lack of several locally important mechanisms (e.g., public services supply and local amenities).

5.4.3 Sensitivity analysis

We are well aware of the limits of our model, a very simplified vision of reality, and of the limits of our calibration. To estimate the robustness of our model, a systematic analysis of the sensitivity of different outputs to different inputs has been carried out. Tab. 5.3 summarizes the elasticities of model output with respect to model inputs.

Apart from those relating to construction costs, all these percentages are close to 0.5% or 1%, which means that numerical uncertainty on urban shape caused by a change in our parameters is equivalent to the uncertainty on the variation of our parameters. There is no parameter for which a small uncertainty can translate into a large uncertainty in model result, which is comforting and suggest that our model results are rather robust.
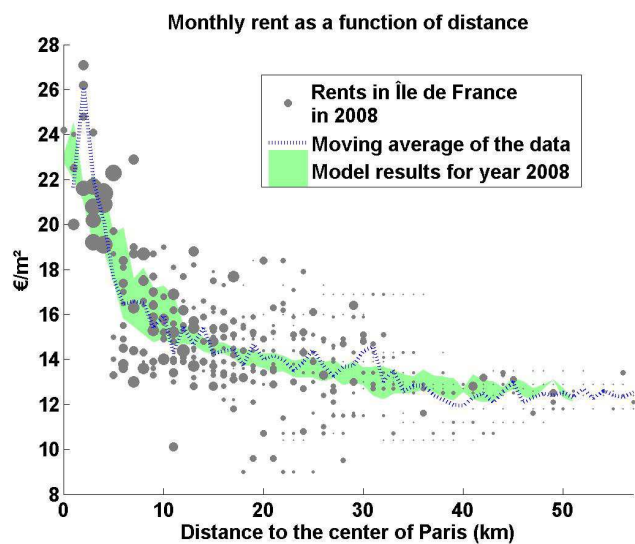
(a) Rents (Data source : CLAMEUR). The model explains 55.1% of the two-dimensional variance of the data.
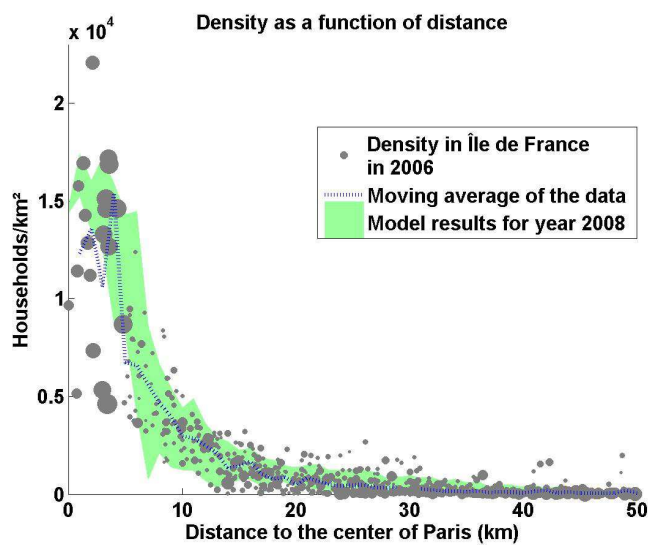

(b) Population density (Data source : INSEE). The model explains 74.7% of the two-dimensional variance of the data.

FIGURE 5.7 – Rents and population density computed by the model (green area) and from data. Dots represent data for individual localities. The dotted line represents the average value of data at a given distance from Paris center.
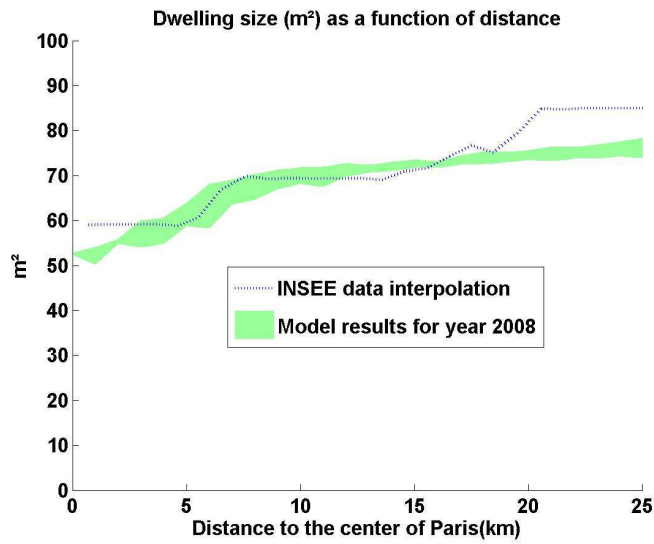
(a) Dwelling size in 2006 (Data source : INSEE and IAU).
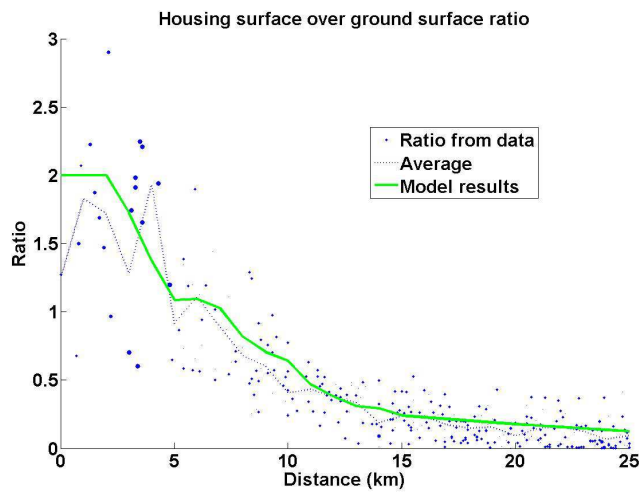
(b) Housing surface over ground surface ratio, computed by the model (plain line) and from data (dots). The dotted line represents the average value at a given distance from Paris center.

FIGURE 5.8 – Dwelling size and housing surface over ground surface ratio, computed by the model (green area) and from data. The dotted line represents the average value of data at a given distance from Paris center.
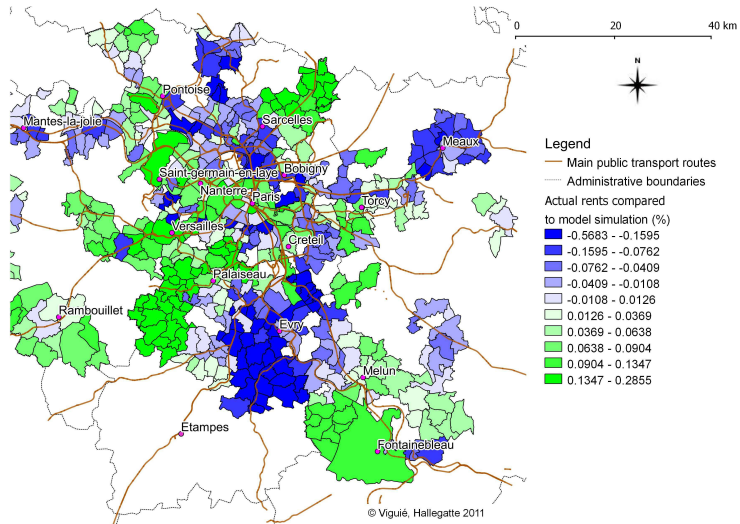
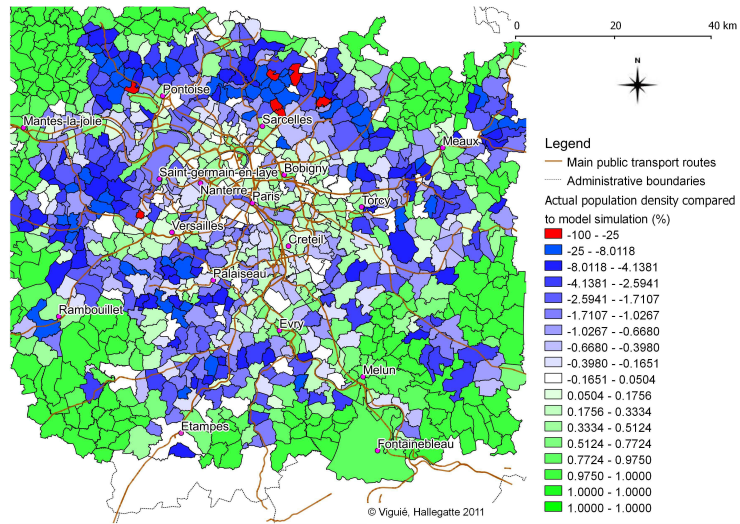FIGURE 5.9 – Difference between simulated rents and actual ones.

FIGURE 5.10 – Difference between simulated densities and actual ones.

	Population	Income	ratio ground surface decicated to housing/total ground surface	Rent determining city border	Fuel price	Time cost near Paris	Duration of the journey when time cost changes	Time cost far from Paris	Coefficient A in construction costs function	Coefficient b in construction costs function	Coefficient β in utility function	Built capital depreciation time	Interest rate
Rent in the center	0.10	0.90	-0.10	0.74	0.10	0.11	0.38	0.05	-0.26	-1.24	-0.50	0.04	0.13
Average rent	0.01	0.90	-0.01	0.94	0.11	-0.27	0.46	0.06	-0.09	-0.26	-0.31	0.01	0.04
Dwelling size in the center	-0.10	0.10	0.10	-0.74	-0.10	-0.11	-0.38	-0.05	0.26	1.24	1.50	-0.04	-0.13
Average accommodation size	-0.04	0.11	0.04	-0.88	-0.10	0.14	-0.40	-0.06	0.13	0.51	1.18	-0.02	-0.06
Density in the center	0.10	-0.10	-0.10	0.74	0.10	0.11	0.38	0.05	-0.26	-1.24	-1.50	0.04	0.13
Average distance to city center	0.43	0.46	-0.43	-1.06	-0.46	1.02	-1.59	-0.26	-0.99	-5.60	1.49	0.14	0.49
Average construction cost per sqm	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.56	-21.79	0.00	0.00	0.00

TABLE 5.3 – Sensitivity analysis. Elasticities of model outputs with respect to model inputs : in each cell is written the percentage of change of the quantity of y-axis when the quantity of x-axis varies by 1%.

5.5 Calibration on London

Results suggest a satisfying correspondence between model results and data points, prompting us to believe that the model is able to represent the main determinants of the urban structure. A rigorous validation will however be only possible by calibrating the model on several cities with different characteristics. This Section presents a calibration on London metropolitan area, and Section 5.6 preliminary tests on other French cities.

5.5.1 Approximations and hypotheses

In our simulations, we make several simplifying assumptions. They are similar to the assumptions which are made when the model is applied to Paris urban area (Section 5.1.2).

First, we suppose that there exists a unique city center, in the geographical center of London, in which all jobs are supposed to be located. Indeed, like in Paris, real estate prices and population density reach a peak at a point that corresponds to the center of London and decrease on a regular basis when one moves away (Fig. 5.11(a) and 5.11(b)).

Second, the city structure must be freely driven by market forces. We explicitly introduce urban constraints in the model, in the form of a limited building height in London. Like in Paris, we also exclude social housing from our field of study, because it is strongly regulated and do not follow market forces.

For the sake of simplification, we also assume that all households have the same size and the same income.

5.5.2 Data and model calibration

As all input data were not available, some input coefficients had to be calibrated, i.e. their value was optimized in a realistic range to make model simulation as close as possible to reality. Table 5.4 lists input data and Tab. 5.5 calibrated parameters.
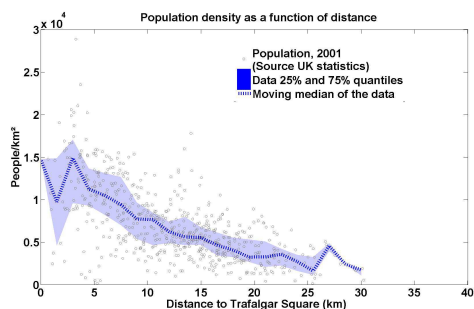
Urban area population   The total population of the urban area is a critical input of our simulations: this population should encompass all people who commute to London. The best approximation I found was given by European Community's ESPON project[16]: 13,709,000 people.

Transport   We used public transport times computed by Alistair Ford in Newcastle University, taking into account long-distance suburban trains but not underground network (Fig. 5.12)[17], and private car travel times assessed using Google Map © online tool.

I used French private car travel costs (per km) as a proxy of English ones. As a proxy of public transport costs, I used 50% of private car travel costs (per km). I added to private car travel costs a daily £ 10 congestion charge. I added a uniform 15 minutes parking time to private car travel, a 10 minutes waiting time to travels by walking only,

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[16]http://www.espon.eu/main/Menu_Projects/Menu_ESPON2006Projects/Menu_ StudiesScientificSupportProjects/urbanfunctions.html

[17]This is due to data availability. At the time of the redaction of this document, subway transport times were in process and could not be used in our analysis.

(a) Median house price as a function of distance.
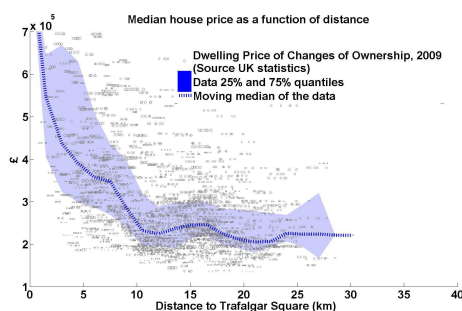
(b) Population density as a function of distance

Figure 5.11: House price and population density in Greater London.

Input data	Value	Source/Comments
Urban area population	13,709,000 people	EPSON, cf. below
Household size	2.3 people per household	UK statistics
Fraction of urbanized ground surface devoted to housing	62%	Value used for Paris urban area
Households income	21,259 £	UK statistics[*]
Transport times and costs in London urban area	cf. below	Cf. below
Cost associated with travel time	Non constant cost, Section 5.3.3	Value used for Paris urban area
Building capital cost	$\delta = 5\%$	Value used for Paris urban area
Built capital depreciation rate	$\rho = 0.5\%$	Value used for Paris urban area
Urbanism constraints	cf. above	Cf. below

[*] Median gross household income: 26,910 £ per year. In London, the average disposable income/gross income ratio is 79%, so in our simulations we use 21,259 £ as disposable median income. (Source: UK statistics)

Table 5.4: Summary of input data

Calibrated parameters	Value	Source/Comments
Share of household income devoted to housing expenses (parameter β in utility function)	50%	Seems high, but reasonable
Coefficients of construction cost function	A=83,242 and b=0.1024	Quite different from the values used for Paris urban area (A=2.0140 and a=0.64)
Rent determining city border	1.9604 £/m^2/month	Much lower than the value used for Paris urban area (12 €/m^2/month)
Price-to-rent ratio	66.6667	
Number of commuting trips per household per day	1.5723	
Parking time and waiting time	15 minutes for private car, 40 minutes for public transport and 10 minutes for walking	
Maximum floor-area ratio	0.5	Much lower than the value used for Paris urban area (which was 2)

Table 5.5: Summary of calibration parameters

and a 40 minutes waiting time to public transport travels. This last figure seems large, but was chosen to reflect also the walking time between the final public transport station and the employment location.

Land use and urbanism constraints   Urban development is not possible everywhere: due to physical constraints or regulations, some places cannot be urbanized. As in Paris, we use existing activity zones (airports, ports and railways), forests, parks and water surfaces are a proxy of places where city development was forbidden or impossible. On the contrary, we considered that agricultural land was not a constraint on city development (cf. Appendix 5.A).

Since 1938, London is surrounded by the Metropolitan Green Belt, where building is strictly controlled. This green belt is not fully taken into account by previous constraint, as it encompasses both forests and agricultural land[18]. I designed and used a rough approximation of the green belt area (Fig. 5.13) and I supposed that building was forbidden in this zone too.

Finally, we used 62% as the maximum fraction of housing surface over total ground surface in places where city development is possible. This value is the floor to ground surface ratio in the center of Paris (cf Section 5.2.1); we used the same value for London.

5.5.3   Simulation results

As shown in Fig. 5.14, the model describes the distribution of housing prices across the city in 2009 quite satisfactorily, when all locations at the same distance from city center

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[18]For instance, the Green Belt does not clearly appear on Fig. 5.23(b) in Appendix 5.A
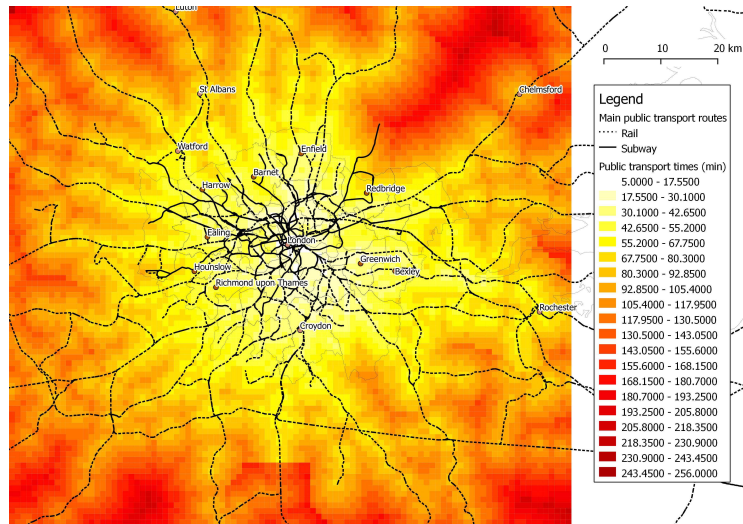
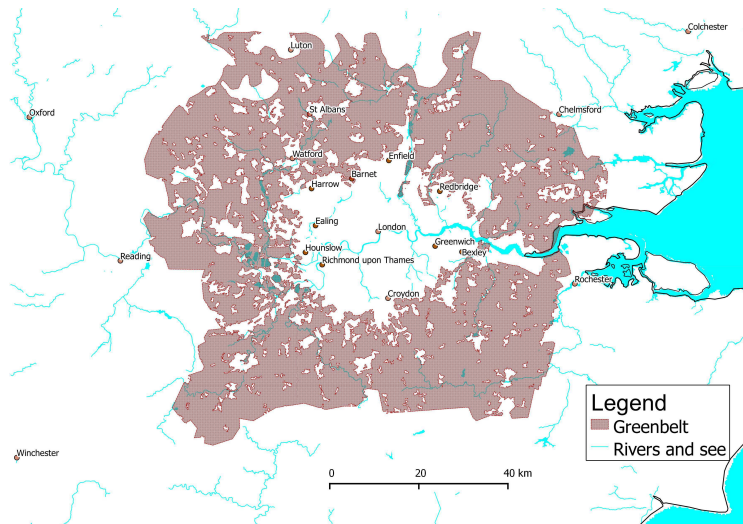Figure 5.12: Public transport times used in the simulation.

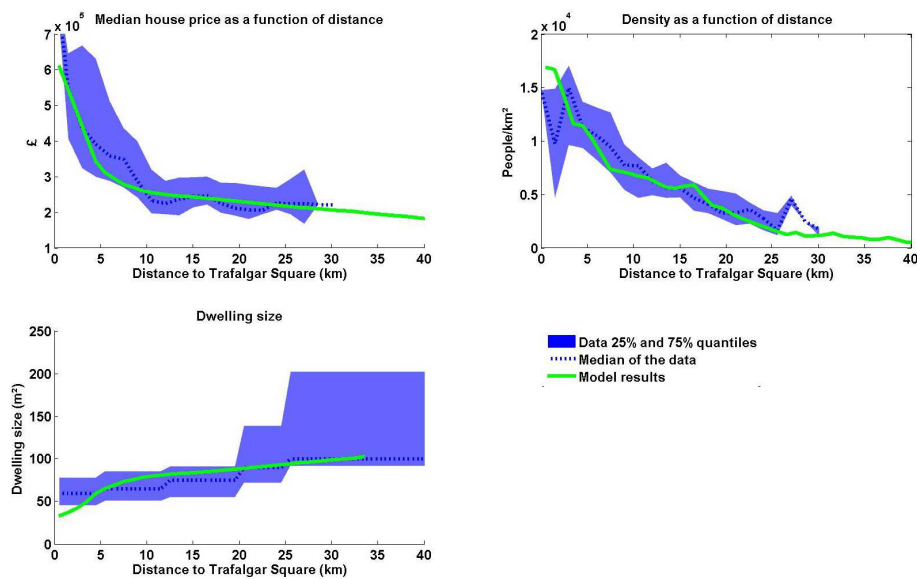Figure 5.13: Approximation of the Metropolitan Green Belt.

Figure 5.14: Comparison between some data and model simulation. Data source: UK statistics.

are averaged. Doing so cancels out other characteristics of the area (e.g., amenities, quality of public services), and the proximity from city center is the major driver of housing prices. There is also a good agreement between the model and data in terms of population density. Similarly, Fig. 5.14 shows a reasonable agreement in terms of dwelling size, even though we have little data on this aspect and the curve representing the data should be considered carefully.

Model and data seem to match well on the urban area scale, even if local differences can be large, due to the lack of several locally important mechanisms (e.g., public services supply and local amenities).

Figure 5.16 presents spatially the difference between simulated population density and actual one. No clear pattern emerges.

In some places, the model highly over evaluates population density. This can be explained by several factors. First, in the simulations, there is no competition between households and firms for land use, leading to a high population density in the City, whereas in reality firms use most of available space there. Second, public transport times we used in our simulations do not take subway into account, leading to reduced differences between places with high subway accessibility and places with low subway accessibility. This could explain the population density over evaluation in Thamesmead East, which is not very populated because it is difficultly reached by subway, whereas adjacent neighborhoods are not.

Figure 5.16 presents spatially the difference between simulated housing prices and actual ones. The model tends to over evaluate housing prices in poor districts and to under evaluate them in rich districts: as shown in Fig. 5.17, there is a correlation between this difference and district average income, showing the importance of developing the model to take into account household heterogeneity (see the Conclusion of this document).
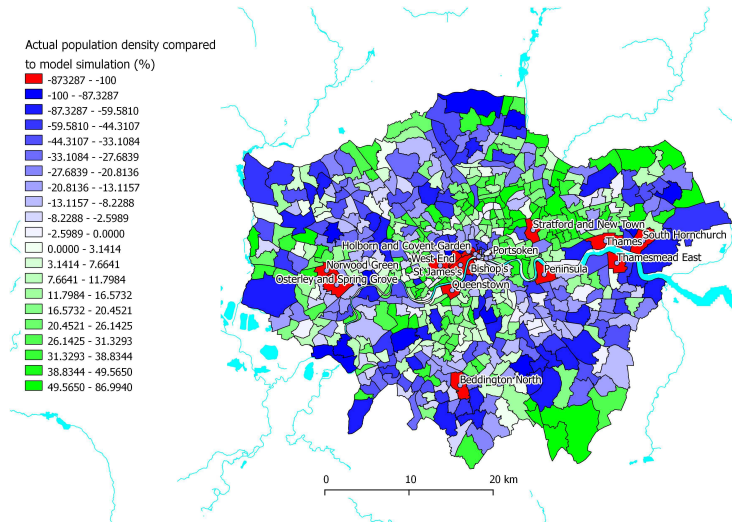
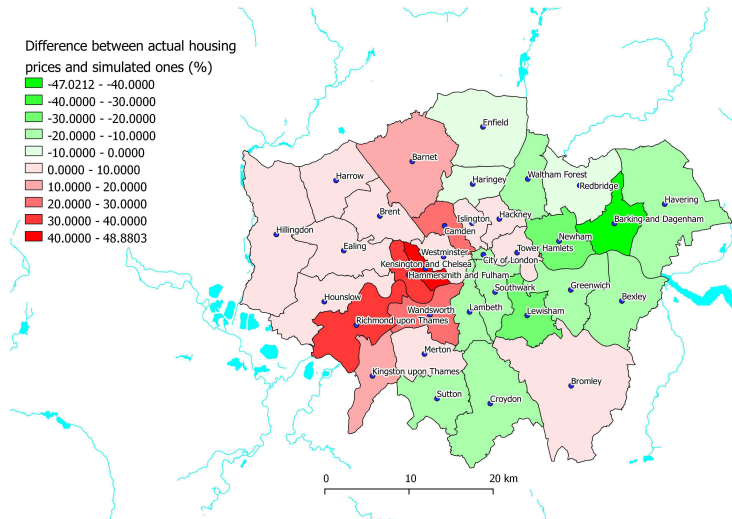Figure 5.15: Difference between simulated density and actual one.

Figure 5.16: Difference between simulated house prices and actual house prices.

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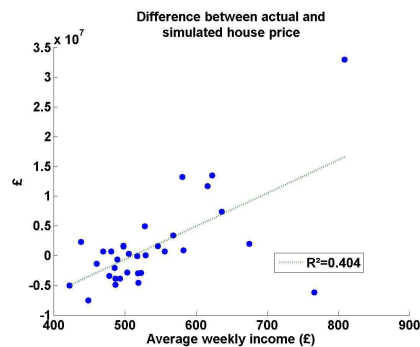**Difference between actual and simulated house price**

Figure 5.17: Correlation between the difference between simulated house prices and actual house prices, and average weekly income.

Urbanized area   As can be seen on Fig. 5.18, the model reproduces well London urban area general shape. The main mismatch is close to the border of the greenbelt, in the north and in the east of the city: in model simulations, this area is urbanized, whereas in reality it is not. Conversely, in several places located close to the green belt border, the model does not capture observed urbanized areas.

Places where the model falsely predicts urbanization are not very well connected to public transport, whereas actual urbanized places tend to be close to train stations: the discrepancy can be explained by the fact that in the simulations long distance public transport costs are too high compared to private car transport costs, leading to city extension in places difficult to reach in public transport, but easy to reach with a private car.

In many urbanized places outside the Green Belt but close to London, like for instance Luton, the model does not predict urbanization. This is related to the broader issue of London metropolitan area limit: in EPSON study, these places were not included in London metropolitan area. Figure 5.19 shows a map of a simulation with a population increased by 25%: in this case, most of Luton is urbanized.

5.6   Calibration on other French cities

To assess to what extent our modeling is valid, we used the model to simulate the 30 biggest French urban areas. Results are shown on Fig. 5.20, 5.21 and 5.22. These are rough estimates, computed using same transport times, costs and land-use constraints as in Paris urban areas. Only urban areas populations, average income and rent determining city border[19] were varied. Rents data come from CLAMEUR database, and, for each municipality, population densities are computed as the total population (source: INSEE) divided by the total area of the municipality, including water areas, forests parks etc. (Source: IGN).

Agreement between model and data is good for several cities (Paris, Lyon, Clermont-Ferrand, Genoble, Rouen, Nancy, Tours, Caen, Orleans, Angers, Dijon, Le Havre) and weak for several others (Saint-Etienne, Metz, Douai, Nice, Nantes, Toulon). However, order of magnitude appears to be correct most of the times.

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[19]Rent determining city border was set equal to the lowest rent inside a circle with a 50km radius, and with its center on the geographical center of the city.
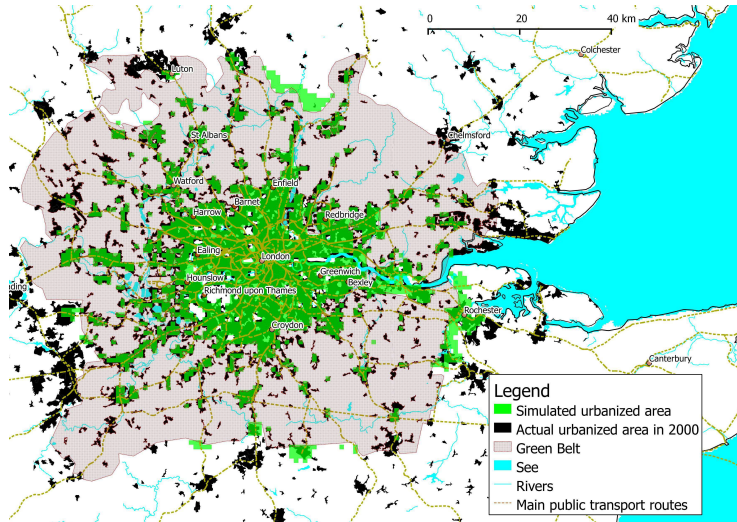
Figure 5.18: Simulated urbanized area in 2000. Actual urban area appears in black (Source: Corinne Land Cover), whereas model simulation appears in transparent green.
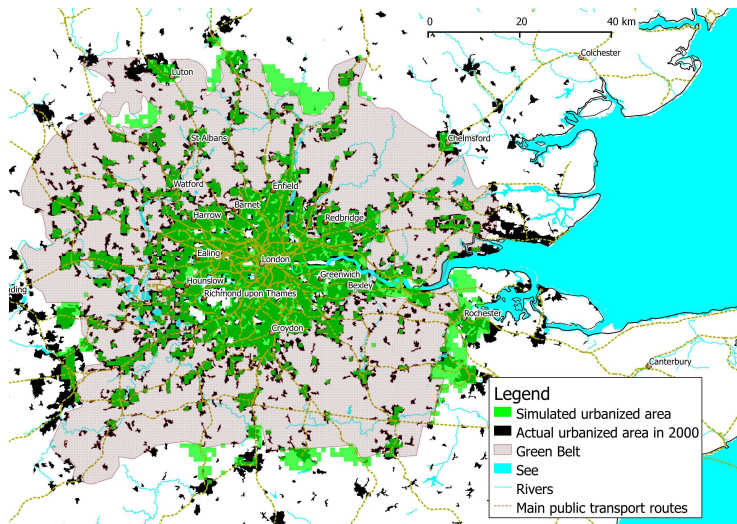
Figure 5.19: Simulated urbanized area in 2000, with 25% more inhabitants than in EPSON study. Actual urban area appears in black (Source: Corinne Land Cover), whereas model simulation appears in transparent green.

A more detailed study, taking into account local transport networks, land-use constraints (e.g. the sea for coastal cities) and city characteristics (e.g. the strong polycentrism of several cities, or the important role played by amenities in coastal cities) is required to refine this analysis, which nevertheless confirms the ability of the model to represent the major mechanisms of urban economics.
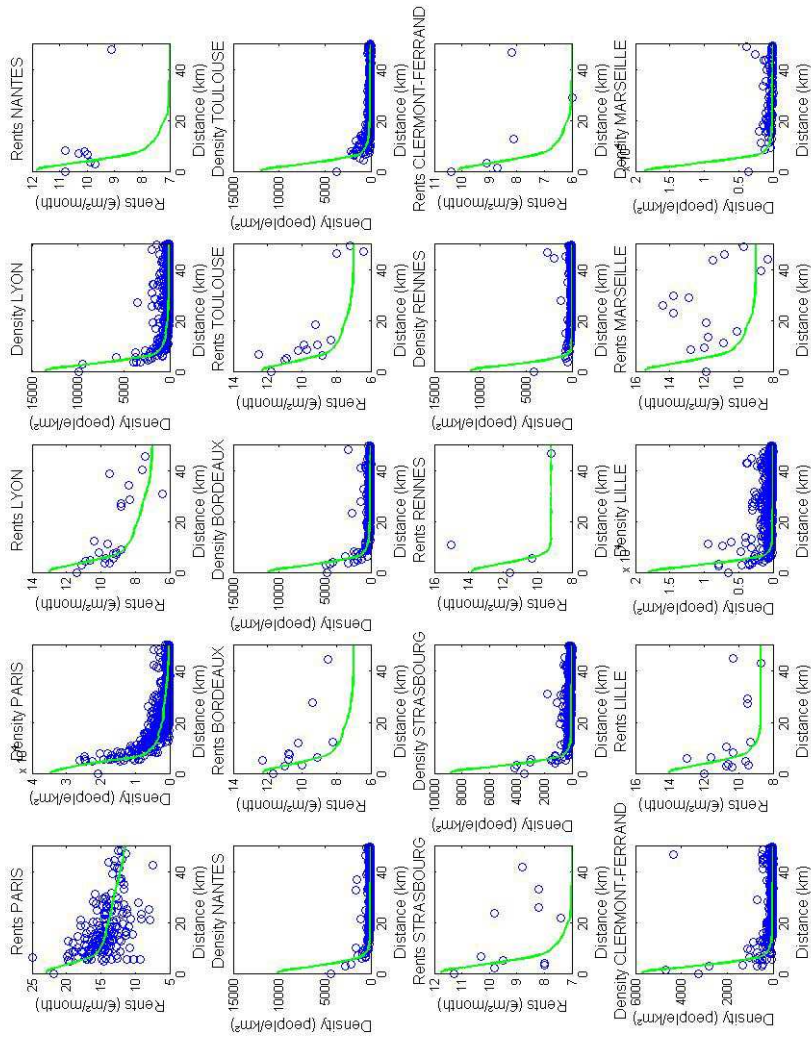
Figure 5.20: Rents and population density for 30 French cities (1/3). Blue point are actual data (Source for rents: CLAMEUR. Source for population densities: INSEE and IGN) and green curve model results. Data points have to be understood as averages over a whole metropolitan area, which can in some cases be large.

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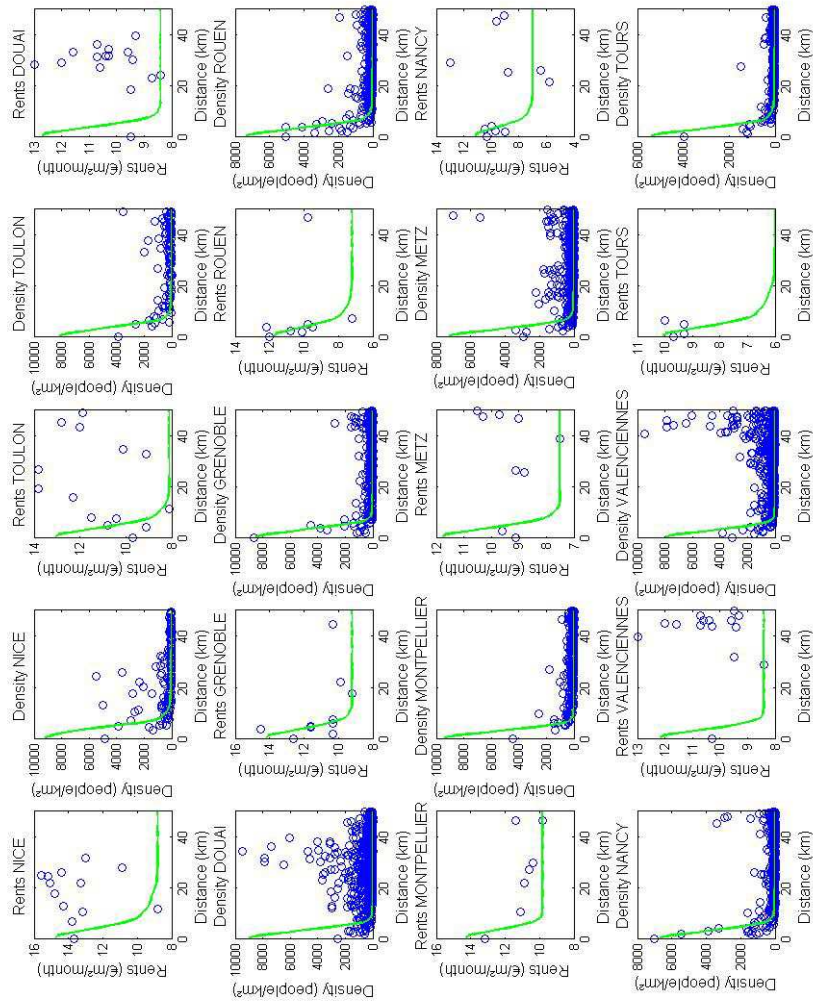
Figure 5.21: Rents and population density for 30 French cities (2/3). Blue point are actual data (Source for rents: CLAMEUR. Source for population densities: INSEE and IGN) and green curve model results. Data points have to be understood as averages over a whole metropolitan area, which can in some cases be large.

108
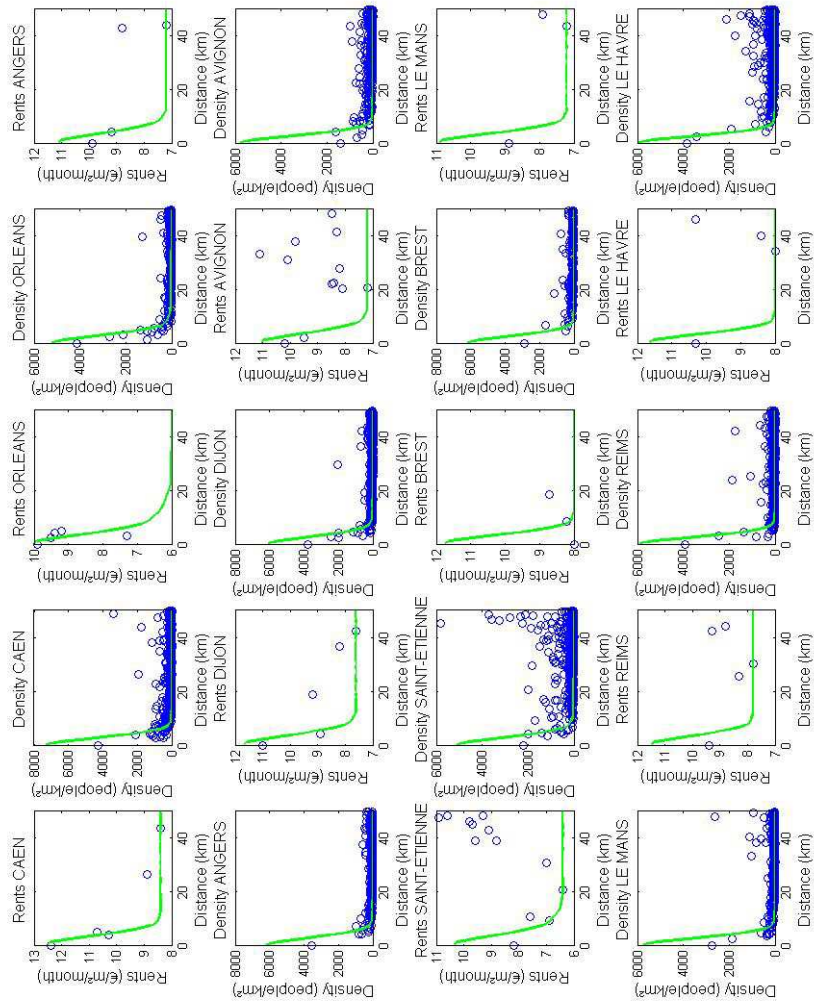
Figure 5.22: Rents and population density for 30 French cities (3/3). Blue point are actual data (Source for rents: CLAMEUR. Source for population densities: INSEE and IGN) and green curve model results. Data points have to be understood as averages over a whole metropolitan area, which can in some cases be large.

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Appendix 5.A   Restricted Land

Restricted land is computed after actual land-use, and is used as a constraint of simulations. We used Corine Land Cover 2006 data (cf. Tab. 5.6 and resulting Fig. 5.23(a) and 5.23(b)).

Free	Restricted	Code clc	Label
Free		111	Continuous urban fabric
		112	Discontinuous urban fabric
		121	Industrial or commercial units
	Activity (black)	122	Road and rail networks and associated land
		123	Port areas
		124	Airports
Free		131	Mineral extraction sites
		132	Dump sites
		133	Construction sites
	Low vegetation (light green)	141	Green urban areas
		142	Sport and leisure facilities
Free		211	Non-irrigated arable land
		212	Permanently irrigated land
		213	Rice fields
		221	Vineyards
		222	Fruit trees and berry plantations
		223	Olive groves
		231	Pastures
		241	Annual crops associated with permanent crops
		242	Complex cultivation patterns
		243	Land principally occupied by agriculture, with significant areas of natural vegetation
		244	Agro-forestry areas
	Forest (dark green)	311	Broad-leaved forest
		312	Coniferous forest
		313	Mixed forest
	Low vegetation (light green)	321	Natural grasslands
		322	Moors and heathland
		323	Sclerophyllous vegetation
		324	Transitional woodland-shrub
		331	Beaches, dunes, sands
		332	Bare rocks
		333	Sparsely vegetated areas
		334	Burnt areas
	Water (blue)	335	Glaciers and perpetual snow
		411	Inland marshes
		412	Peat bogs
		421	Salt marshes
		422	Salines
		423	Intertidal flats
		511	Water courses
		512	Water bodies
		521	Coastal lagoons
		522	Estuaries
		523	Sea and ocean

Table 5.6: Summary of calibration parameters
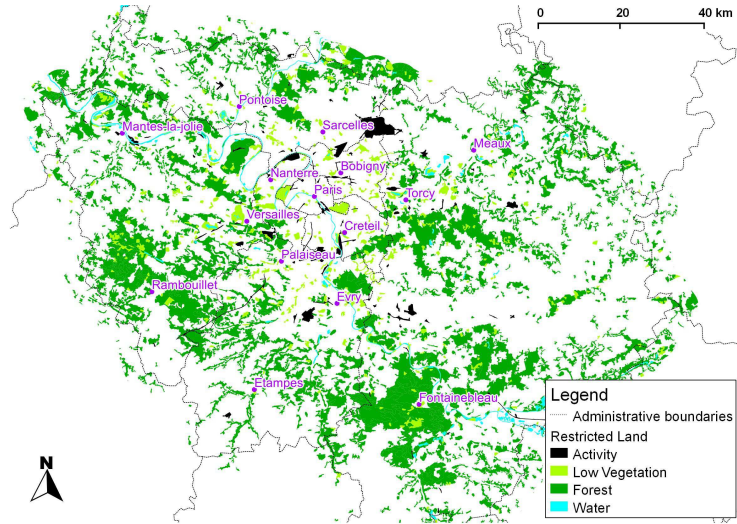
(a) Map of restricted areas in Ile de France. Black areas are airports, Gennevilliers port and railways. Source: Corine Land Cover 2006.
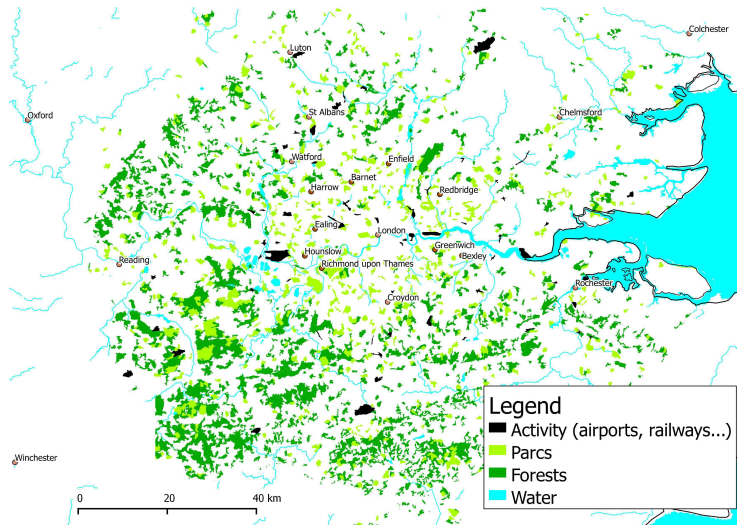
(b) Map of restricted areas in Greater London. Source: Corine Land Cover 2000.

Figure 5.23: Map of restricted areas in Ile de France and Greater London (legend: cf. Tab. 5.6).

Chapter 6

A dynamical model to understand city evolution

We can use the model we have presented in Chapter 5 to simulate a city in the past or in the future, and to study its evolution. However, this model is computing an equilibrium, an hypothesis which is questionable: when population, transport prices, or income vary, housing infrastructure cannot adapt rapidly to changing conditions (Gusdorf et al., 2008).

A first possibility is to separate built environment adjustment from rents and population density adjustment. When analyzing a policy, since buildings adjust much more slowly than rents, we can first compute what a pseudo-equilibrium state where buildings have not changed, but where rents and population density have adjusted (we call it "medium-term"). This state will be different from the equilibrium state when buildings have also been adjusted (we call it "long-term"). This approach, initiated by Gusdorf and Hallegatte (2007a), enables to analyze some transitory effects created by the policy, before equilibrium is reached, and Chapter 7 shows an example of such an analysis.

However, how much time is exactly involved in the definition of "medium-term" and "long-term" remains unclear, and it is not possible to study the effect of a continuous evolving variable such as transport prices evolution, or policy, such as a carbon tax increasing over time. To address this issue, we have developed another model which takes explicitly into account this dynamics and describes cities as non-equilibrium systems. It is based on the same philosophy as the macroeconomic model NEDyM (Hallegatte et al., 2007b): each equilibrium (e.g. housing supply equals demand) is replaced by dynamic equations describing the adjustment process (e.g. rents increase when housing demand exceeds supply).

Section 6.1 first presents this model, and Section 6.2 analyzes the simulation of Paris urban area evolution, since 1900. Finally, Section 6.3 compares the simulation made by the two models.

6.1   NEDUM-2D

6.1.1   Principle of the model

NEDUM-2D (Non-Equilibrium Dynamic Urban Model) has been designed to capture the dynamics of urban systems, and the importance of inertia, while relying on

the mechanisms of urban economics. It is based on the model "NEDUM" developed in CIRED by François Gusdorf and Stéphane Hallegatte (Gusdorf and Hallegatte, 2007a,b; Gusdorf et al., 2008), but differs on several important aspects, especially because it had to be able to take into account the effect of a global change in income or population. It also had to be able to describe an actual city, and be coherent with our calibration in Chapter 5.

This model describes the evolution of 4 state variables (defined everywhere in the city): population density, dwelling size, rents and floor-area ratio. the evolution of each of these variables is described by a differential equation, with its own time constant. All the other variables of the city (e.g. owner's income, vacancy rate of dwellings etc.) are computed at each time according to these 4 state variables: no other variable than the 4 state variables evolves with its own inertia.

The logic behind the model is the following: at each time step, a "pseudo-equilibrium" value is computed for the 4 state variables. This "pseudo-equilibrium" value is the value toward which each state variable will evolve. It depends on the model input, but also on the value of the state variables. Between this time-step and the following, state variables will evolve towards their "pseudo-equilibrium" value (each state variable has its own inertia, and they may not converge at the same speed). At the following time step, new "pseudo-equilibrium" values are computed. They can be identical to the last ones, or can be different because the value of the state variables has changed, or because model inputs are different (e.g. the total population of the city has changed). State variables will now evolve towards these new "pseudo-equilibrium" values etc.

Pseudo-equilibrium values are computed such that, if model inputs do not evolve any more, state variables converge towards the actual equilibrium values.

6.1.2   brief presentation of NEDUM-2D

Here is a brief presentation of the model mechanism. A complete description with the full set of equations, is available in Appendix 6.A.

6.1.2.1   Households behavior

We assume that households earn an income Y, and choose their housing consumption and location depending on the rents $R(r)$, as described hereafter:

- Households living at location r adjust their housing service consumption per capita q so as to increase their utility level $u(r) = U(z(r), q(r))$ (Appendix 6.A.1): taking rent level $R(r)$ as given, households increase or decrease the size of their flats so as to maximize their utility (Appendix 6.A.2). Adjustment in housing service consumption per capita is also attained through changes in the size and composition of households, for example through changes in collocation practices, or changes in the age at which children leave their parents' home.

- Households can change locations: the ones living at location r may choose to stay or move to another location (Appendix 6.A.3). We assume they are willing to move when their local utility level $u(r)$ is under the average utility level $\bar{u}$ throughout the city: households living at locations where $u(r) \leq \bar{u}$ source are attracted to places where $u(r) \geq \bar{u}$.

Of course, the processes considered here are active in parallel: changes in flat sizes occur simultaneously with location changes, when households leave one flat to another.

The changes are physically constrained by the characteristics of housing service supply: households can move only if there are unoccupied flats at their target location; they can increase their flat size only if there is a local excess of housing service supply.

Moves of households and changes in flat sizes cannot happen instantaneously, for instance because it takes previous "time" to find a new place to live. The respective inertias of these mechanisms are accounted for by specific characteristics timescales τ_q and τ_n (see Eqs. 6.5 and 6.9). The intensity of these mechanisms depends in each case on the increase in utility level that households expect from these evolutions: the higher is the relative difference between $u(r)$ and $\bar{u}$ source for instance, the more households are willing to move to location r.

6.1.2.2   Rent curve dynamics

Rent level $R(r)$ evolves in reaction to local supply and demand of housing service $H(r)$ (Appendix 6.A.4): demand is expressed by the number of households $n(r)$ living at this location and consuming an amount of housing service $q(r)$, and by the number of households willing to move to or from this location:

- Rent level decreases if demand is lower than local supply, that is, if existing buildings are not fully occupied.

- If buildings at location r are fully occupied, rent levels increase if inhabitants want to increase their consumption of housing service, or if there are outside households willing to move to this location.

The orders of magnitude of these evolutions are determined by the relative difference between local demand and supply of housing service. Moreover, we assume that, for institutional reasons, housing rents do not clear the housing market instantaneously. The inertia of rent levels evolution is characterized in the model by the timescale τ_R.

6.1.2.3   Housing production

Buildings depreciate in urban systems, and are renewed or rebuilt by developers in reaction to rental profitability. We suppose that half of them have a myopic behavior (they make investment decisions as if they were at a stationary state of equilibrium), and that the others make anticipations, and compares rents to rents that households would pay in an equilibrium state where all would have the same utility $\bar{u}$. Since construction takes time, financial investments are transformed into buildings with a time lag τ_H (see Eq. 6.26).

6.2   Calibration on Paris urban area

It is possible to calibrate this model on a city: this lead to some specific issues, coming from data availability, from some theoretical questions, as well as from some technical issues due to the structure of NEDUM-2D.

6.2.1   Data and calibration

To calibrate this model, we need same data as in Chapter 5, but over a wide time-period instead of at a single moment in time. We also need to calibrate time constants, which is particularly difficult. All data used in the simulations are summed up Tab. 6.1.

To compute generalized transport prices, we used data about walking times, actual transport times and prices in public transport (underground, regional trains and suburban trains) and private transport (during rush hours, for an average car). At each location, the generalized transport cost is computed for each transport mode, and a logit weighting is used to compute the modal shares.[1] In the simulations, changes in public and private transport prices lead therefore to modal shifts.

We suppose in the simulations that construction costs and value of time evolve, over time, proportionally to households average income. This a strong hypothesis, with important implications on model results (cf. Chapter 8).

Concerning the cost of time, our hypothesis is coherent with the relevant literature (see for instance Zamparini and Reggiani, 2007). However, it should be noted that technological innovations that make travel more comfortable reduce the cost of time (i.e. the monetary equivalent of spending one minute in traveling, expressed as a fraction of the hourly net wage). Therefore, a constant trend towards more comfortable means of transport would result in a cost of time increasing less than proportionally to income. Empirical studies have captured this phenomenon (Shires and de Jong, 2009). Here, we neglect this phenomenon (cf. Chapter 8 for a discussion of the consequences).

It proves difficult to find analyses of long term evolution of construction costs over time. To the authors' knowledge, no data exist in the relevant literature. If construction price indexes are measured in many countries, they are generally measured for constant-quality dwelling, and do not take into account the evolution of preferences and construction norms. It is therefore difficult to assess how construction costs have evolved in the past. We suppose that these costs evolve proportionally to households income.

6.2.2 Calibration

Table 6.2 present the numerical coefficients we used in our simulations. In absence of adequate data for some parameters, for instance the cost of time and construction costs, these parameters have been calibrated on the Paris structure in 2008 (Viguié and Hallegatte, 2011).

The calibration of parameters τ_H, τ_n, τ_R and τ_q is particularly difficult. In this analysis, we assume that the timescale of population density and rents evolution is 3 year, whereas for dwelling size evolution it is 20 years. We also assume that building construction takes approximately 2 years. We have therefore chosen $\tau_R = \tau_n = 3$ years, $\tau_q = 20$ years and $\tau_H = 2$ years.

Similarly, it is difficult to assess the depreciation rate τ_{dH} of Paris buildings. We use here a depreciation timescale of 100 years (consistent with Wilhelmsson (2008), for instance).

Considering the uncertainty in these parameters, we carried out a sensitivity analysis, varying each parameter independently, or simultaneously. We found that the qualitative results and order of magnitude presented in this paper are unchanged within a broad range of values (e.g., from 1 month to 20 years for τ_H, τ_n and τ_R, from 1 month to 100 years for τ_q, and from 50 to 200 years for τ_{dH}).

We have chosen 1.5 as the value of the maximum floor-area ratio in the center of Paris. This value may seem low as most buildings in Paris have approximately 6 floors, which would induce a ratio of about 6 at the center of Paris. However, our ratio

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[1]More rigorously, at each location, the logit weighting is computed on each price divided by the minimum price at this location.

Input data

Urban area population	French census figures for Paris urban area until 2008 and demographic scenario for 2009-2100 (Section 8.1.2).
Households average income	Households disposable income (Source: IN-SEE and J. Friggit) until 2008 and techno-economic scenario for 2009-2100 (Section 8.1.1).
Fraction of ground surface devoted to housing	Source: Corine Land Cover and airport noise zones (Source: IAU). In places where building is possible, the maximum fraction of ground surface devoted to housing is 62%
Maximum floor-area ratio in the center of Paris	1.5 (cf. Section 6.2.2)
Transport times in Paris urban area	Data used in Rouchaud and Sauvant, 2004
Public and private transport prices	Data used in Nadaud and Hourcade, 2009 until 2008 and techno-economic scenario for 2009-2100 (Section 8.1.1). We only deal here with perceived travel cost, and not with real travel cost which would also include vehicle amortization.
Interest rate	$\delta = 5\%$
Built capital depreciation time	$\tau_{dH} = 100$ years
Dwelling size evolution time constant	$\tau_q = 20$ years
Rent evolution time constant	$\tau_R = 3$ years
Population density evolution time constant	$\tau_n = 3$ years
Housing stock evolution time constant	$\tau_H = 2$ years

Table 6.1: Summary of main input data

Calibrated parameters

Households utility function parameter (6.A)	$\alpha = 0.7$
Coefficients of construction cost function (6.A)	$A = 2.0140$ and $a = 0.36$ in 2008 (6.2.1). Coefficient A evolves proportionally to $(income)^{-(1-a)}$
Cost associated with travel time	cf. 6.2.1 and 5.3.3
Rent determining city border	$R_0 = 12\,€/m^2$ in 2008, and evolution proportional to income.
Logit factor used to compare different transport modes at each location	$factor = 4$

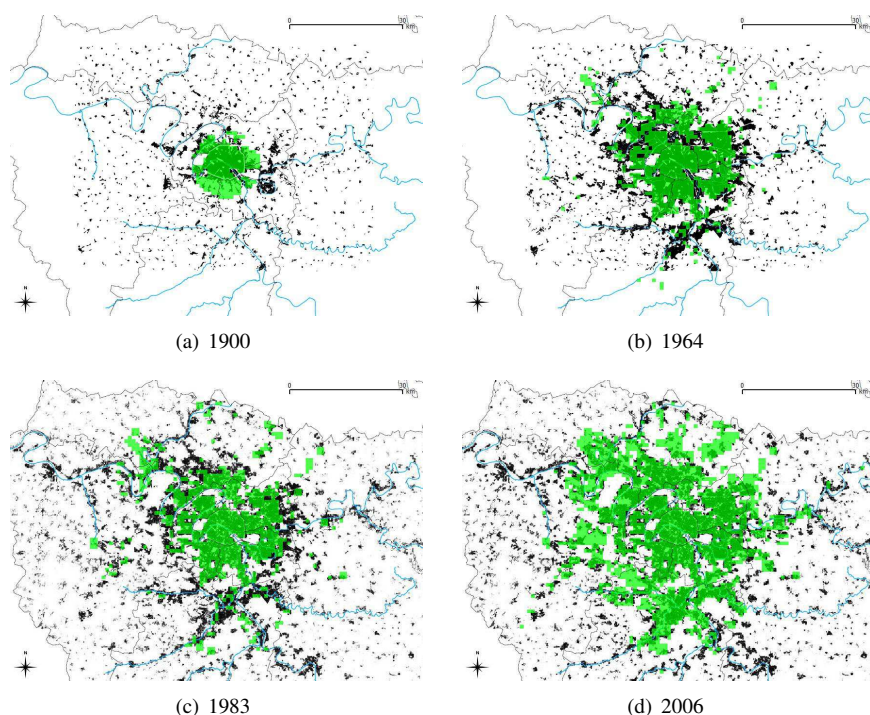Table 6.2: Summary of calibration parameters

Figure 6.1: Simulated urbanized area compared to actual urbanized area. Actual urban area appears in black (Source: Corinne Land Cover and IAU), whereas model simulation appears in transparent green.

is only taking into account housing surface, and not the total built surface, and the discrepancy is simply caused by built surface intended for purposes other than housing (it includes, on the one hand, corridors and lobbies in buildings dedicated to housing and, on the other hand, all buildings not dedicated to housing: offices, shops, museums, train stations, office buildings, schools, universities, etc.).

6.2.3   Analysis of the simulations

6.2.3.1   Urban area evolution

As can be seen on Fig. 6.1(d), the model reproduces well the current Paris urban area. The main mismatch is in the west (Mantes la Jolie) and in the south of the urban area (Melun), where the model does not capture observed urbanized areas. These two zones correspond to cities which were built long before being included in Paris urban area, and are important employment centers on their own, whereas the model only represents built areas due to Paris urban area sprawl.

Contrary to simulation presented in 5.4.1, airport noise zone (source: IAU) have been taken into account: building is possible in these zones until 1985. After this year, new constructions are forbidden, but existing buildings remain in place.

It is possible to use this model to simulate city evolution from 1900 to 2008. For instance, Fig. 6.1(a), Fig. 6.1(b) and Fig. 6.1(c) compare simulated urban area with actual urbanized area, in 1900, 1964 and 1982, respectively. Because of the lack of

data, we used the same transport network as in 2008 to do these three simulations, and the description of the city in 1900 is not as good as for the following years[2]. However, large-scale trends between 1900 and 2008 are well described, suggesting that the model captures the main determinants of city shape evolution.

6.2.3.2 Internal city structure

The urban structure in dynamical simulations appears to be very close to the urban structure computed with the equilibrium model (Section 5.4.2). Indded, since Paris urban area has a regularly growing population, it is never very far from its equilibrium state (i.e. the state simulated when the input parameters are held constant). A calibration on a shrinking city, with a decreasing population, would therefore be of great interest (cf. the conclusion of this document).

As shown in Fig. 6.2(a) the model describes the distribution of rents across the city in 2008 satisfactorily. In two dimensions, the model explains 51.8% of the variance in rents. When all areas at a given distance from the center are averaged, the odel explains 89.5% of the uni-dimensional variance. Figure 6.2(b) shows that there is also a good agreement between the model and data in terms of population density. The model explains 77.2% of the two-dimensional variance in population density, and 95.9% of the uni-dimensional variance. Similarly, Fig. 6.3(a) shows a reasonable agreement in terms of dwelling size, even though we have little data on this aspect. Finally, Fig. 6.3(b) shows that this agreement holds over time, at least since the 1980's.

Model and data seem to match well on the urban area scale, even if local differences can be large, due to the lack of several locally-important characteristics (e.g., public services supply and local amenities), like for the static model.

6.2.3.3 Transport

Data on past transport times and costs are difficult to find, and we therefore had to use rough estimates for transport before the 1960's. As can be seen on Fig. 6.4, after 1960, simulated average daily commuting transport time is close 1.1 hour, i.e. Zahavi's estimate (cf. Section 4.1.1.2 in Chapter 4). Before 1960, commuting time is much higher, because in our simulations, a large fraction of commuters walks to go to work, due to the high price of private car and subway transport. We have not included in our model bus and tramway networks, which were of great importance at that time: including these two transport means would enable to get more realistic results.

Simulated value for present-day public transport modal share is very close to actual one (cf. Fig. 6.5). We have found no reliable value for past modal shares, but it can be expected that, as for transport times, results before the 1960's could be improved by a better description of past transport networks.

Finally, Fig. 6.6 shows the evolution of average home-work distance in Île de France. Our simulation overestimates this distance (by roughly 15%), but order of magnitude and evolution tendency seem right.

6.2.3.4 Rents and real estate prices

Figure 6.7 shows the simulated evolution of rents in Île-de-France compared to national rent evolution index, both divided by income evolution. Our simulation does not

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[2]For instance, bus and tramway networks are not modeled, whereas they were of great importance at the beginning of the 20th century.

Monthly rent as a function of distance
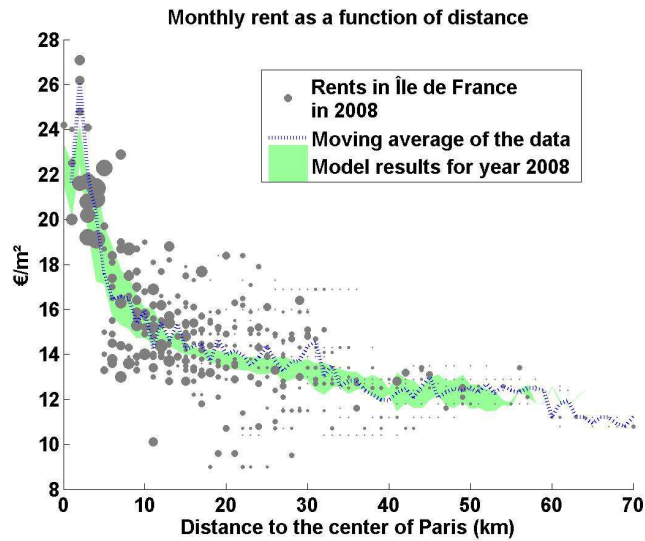
(a) Rents (Data source: CLAMEUR). The model explains 42.2% of the variance of the data.

Density as a function of distance
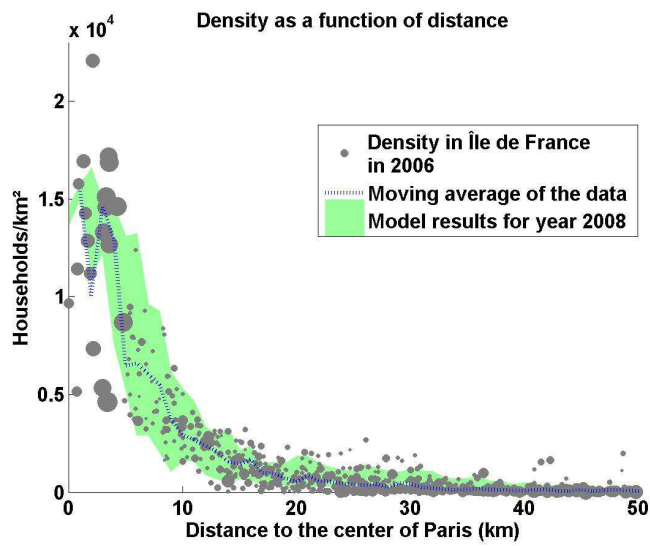
(b) Population density (Data source: INSEE). The model explains 67.4% of the variance of the data.

Figure 6.2: Rents and population density computed by the model (plain line) and from data. Dots represent data for individual localities. The dotted line represents the average value at a given distance from Paris center.

Dwelling size (m²) as a function of distance

(a) Dwelling size in 2006 (Data source: INSEE and IAU)
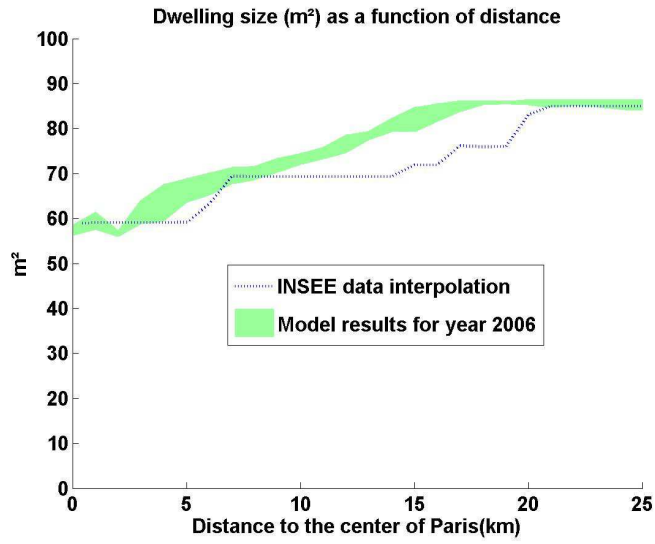
Average dwelling size
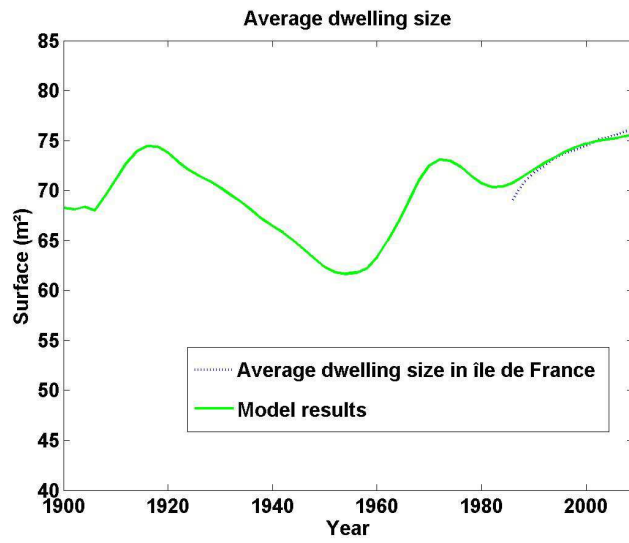
(b) Dwelling size Evolution (Data source: INSEE and IAU).

Figure 6.3: Dwelling size computed by the model (plain line) and from data.
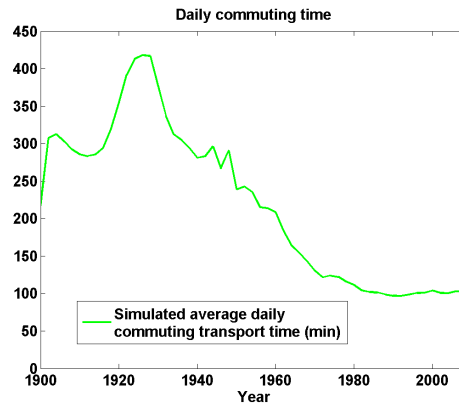
Figure 6.4: Average daily commuting transport time, to be compared to Zahavi's estimate (1.1 hour).
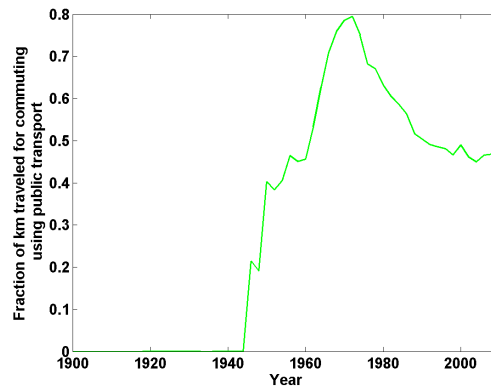
Figure 6.5: Public transport modal share for commuting trips. Actual data for 2002 is 46.63 % (Source: DREIF).
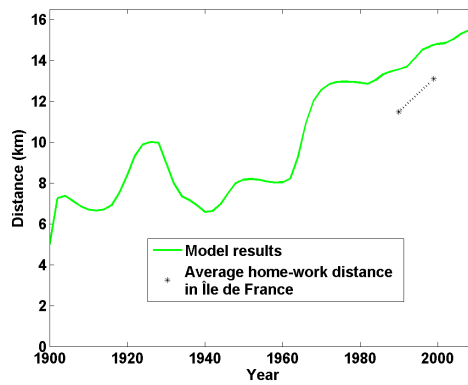
Figure 6.6: Average home-work distance in Île de France. Source of historic data: INSEE, figure computed after population census data.

Rent evolution
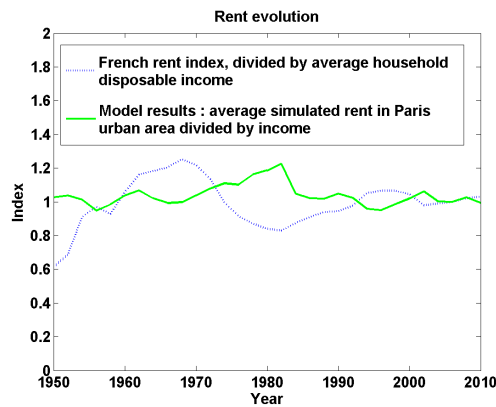
Figure 6.7: French rent index divided by income per household. Source of historic data: J. Friggit, after rent component of the consumer price index, INSEE.

Home price index divided by income per household
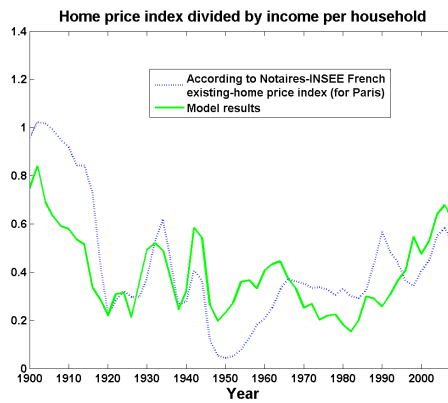
Figure 6.8: Home price index divided by income per household, in Paris. Source of historic data: J. Friggit, after Notaires-INSEE French existing-home price index.

reproduces the oscillations of this ratio, but the overall tendency of to remain close to 1 is captured.

Figure 6.8 presents a similar comparison using real estate prices in Paris, instead of rents level. Simulated "real-estate index" has been computed by dividing simulated rents by historical long-term interest-rates (Source: J. Friggit)[3]. Here, again, model does not reproduces historical oscillations, but evolution tendencies are correct. It should be noted that before 1950, rents in France were largely constrained and not market driven. The apparent good coherence between model simulation and real estate prices evolutions before 1950 should therefore be considered with caution.

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[3]All data provided by J. Friggit can be freely downloaded on `http://www.cgedd.developpement-durable.gouv.fr/home-prices-in-france-1200-2011-r137.html`.

6.3 Conclusion

As explained in Chapter 3, prospective studies that explore various possible future evolutions of cities are required to design the best climate policies. City scenarios designed to support urban planning do exist, but these scenarios are not connected to global scenarios, in which global environmental change can be represented. Moreover, they usually consider time horizons of 30 years or less (cf. for instance Lefèvre, 2009, or studies listed in Haase and Schwarz, 2009; a noticeable exception is Solecki and Oliveri, 2004).

Using, as far as possible, only the most fundamental economic principles, which remain valid over the long term, our NEDUM-2D model appears to be able to reproduce the main tendencies of past Paris urban area evolution, suggesting that this tool can be used to simulate such long-term scenarios: such an exercise will be carried out in Chapter 8. This model also remains tractable and coherent with requirements of Section 4.3 in Chapter 4.

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Appendix 6.A   Equations of NEDUM-2D model

This appendix sets up the formal representation of the mechanisms described in Section 6.1.2.

6.A.1   Utility function

As in Viguié and Hallegatte, 2011, we model the household trade-off using the following utility function:

$$U(r) = Z(r)^\alpha q(r)^\beta \tag{6.1}$$

where r is the location in the city, α and β are coefficients ($\alpha + \beta = 1$), $q(r)$ the surface of the households' dwelling and $Z(r)$ the money remaining after the household has paid its rent and a commuting round-trip per day to the center of Paris. The cost of transportation includes the monetary cost of transportation and the cost associated with the trip duration[4]. Such a functional form is consistent with the fact that the share of households' income devoted to housing expenditures is relatively constant (Davis and Ortalo-Magne, 2010). Households' income constraint reads:

$$Y = Z(r) + q(r) \cdot R(r) + T(r) \tag{6.2}$$

where Y is household income and is constant ($\forall r, Y(r) = Y$), $R(r)$ is the rent per square meter, and $T(r)$ transportation costs (monetary cost added with time cost).

6.A.2   Housing service per household

We assume that households permanently adapt their housing-service consumption to prices so as to increase their utility level to prices. Given the location r, the amount of composite goods consumed is strictly dependent on housing choices: $Z(r) = Y - T(r) - q(r) \cdot R(r)$. We have, therefore:

$$U(r) = [Y - T(r) - q(r) \cdot R(r)]^\alpha \cdot q(r)^\beta \tag{6.3}$$

Using this function, we consider that households can adjust their level of housing service consumption so as to improve their utility level: taking rent level $R(r)$ as given, households increase or decrease the size of their flats so as to maximize their utility. Adjustment in housing service consumption per capita can also include changes in the size and composition of households, for example through changes in flat-sharing practices, or changes in the age at which children leave their parents' home.

A household maximizes its utility if and only if:

- Its share of income devoted to housing service is equal to β: $q^*(r) \cdot R(r) = \beta(Y - T(r))$

- Its share of income devoted to composite good is equal to α: $Z^*(r) = \alpha(Y - T(r))$

It is rational for the inhabitants to make their consumption of housing service tend to $q^*(r)$. Of course, an increase in housing consumption is authorized if and only if such an increase is physically possible, i.e. if there is available housing at this location.

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[4]We consider the cost associated with the trip duration as an actual loss of income.

Changes in flat sizes cannot happen instantaneously, for instance because it takes "time" to find a new place to live. The inertia of this mechanism is accounted for by the timescale τ_q.

Let $\Psi(r)$ be the number of unoccupied dwellings at each location:

$$\Psi(r) = H(r) - q(r) \cdot n(r) \tag{6.4}$$

The dynamics of $q(r)$ is given by:

$$\frac{dq(r)}{dt} = \begin{cases} \frac{1}{\tau_q}(q^*(r) - q(r)) = \frac{1}{\tau_q}\left(\frac{\beta(Y-T(r))}{R(r)} - q(r)\right) & \text{if } \Psi(r) > 0 \text{ or } q^*(r) < q(r) \\ 0 & \text{if } \Psi(r) = 0 \text{ and } q^*(r) > q(r) \end{cases} \tag{6.5}$$

6.A.3 Moving throughout the city

Households can change locations: the ones living at location r may choose to stay or move to another location. We assume they are willing to move when their local utility level $u(r)$ is under the average utility level $\bar{u}$ throughout the city: households living at locations where $u(r) \leq \bar{u}$ source are attracted to places where $u(r) \geq \bar{u}$.

Let $w(r)$ be a weighting function[5], which compares utility level $u(r)$ to $\bar{u}$. We can define:

- if $u(r) \leq \bar{u}$, $m^-(r) = w(r) \cdot n(r)$ is the number of households willing to leave

- if $u(r) \geq \bar{u}$, $m^+(r) = w(r) \cdot \Psi(r)$ is the number of attractive unoccupied dwellings

We have now to take into account city population variation. We know at every time step the population that the city should be POP_{exo}, and the population in the simulated city is POP. Let us define Δ as the difference between the two populations: $\Delta = POP_{exo} - POP$. Let us suppose now that newcomers only choose to locate in areas where utility is bigger than $\bar{u}$: the total aggregated demand of dwellings is equal to:

$$D = \int_{u(r)<\bar{u}} m^-(r)dr + \max(\Delta, 0) \tag{6.6}$$

and the aggregated supply of dwellings:

$$S = \int_{u(r)<\bar{u}} m^+(r)dr - \min(\Delta, 0) \tag{6.7}$$

There is a priori no reason why the demand for moves should equal the supply of available housing. The relationships giving the moves $\mu(r)$ meet these physical constraints:

$$\mu(r) = \begin{cases} m^+(r) \cdot \min(1, D/S) & \text{if } u(r) > \bar{u} \\ m^-(r) \cdot \min(1, S/D) & \text{if } u(r) \leq \bar{u} \end{cases} \tag{6.8}$$

As for changes in flat sizes, moves of households cannot happen instantaneously. The inertia of this mechanism is accounted for by the timescale τ_n.

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[5]We have chosen $w(u) = \frac{2}{\pi}\arctan(\alpha|\frac{u-\bar{u}}{\bar{u}}|)$ where $\alpha = \frac{1}{5\%}\tan(\frac{\pi}{2}.95\%)$, so that $w(u) \geq 95\%$ when the difference between u and $\bar{u}$ is bigger than 5% of $\bar{u}$.

The number of households living at location r evolves according to the moves:

$$\frac{dn(r)}{dt} = \frac{1}{\tau_n}\mu(r) \tag{6.9}$$

6.A.4 Rent curve dynamics

Rent level $R(r)$ evolves in reaction to local supply and demand of housing service $H(r)$. Demand is expressed by the number of households $n(r)$ living at this location and consuming an amount of housing service $q(r)$, and by the number of households willing to move to or from this location:

- Rent level decreases if demand is lower than local supply, that is, if existing buildings are not fully occupied.

- If buildings at location r are fully occupied, rent levels increase if inhabitants want to increase their consumption of housing service, or if there are outside households willing to move to this location.

The orders of magnitude of these evolutions are determined by the relative difference between local demand and supply of housing service. Moreover, we assume that, for institutional reasons[6], housing rents do not clear the housing market instantaneously. The inertia of rent levels evolution is characterized in the model by the timescale τ_R.

Landlords decrease their rents when all dwellings are not occupied, and increase them when demand is bigger than dwelling supply. Let

$$n^*(r) = n(r) + \max(\mu(r), 0) + n_{virtual}(r) \tag{6.10}$$

be the number of households living or willing to leave at a certain location in the city. It is the sum of the number of inhabitants living at this location $n(r)$, the number of households about to move to this location $max(\mu(r), 0)$, and the number of households, $n_{virtual}(r)$, who would like to live in this location, but cannot because there are not enough available dwellings.

Let us define the number of dwellings in the attractive locations by:

$$m_{rent}^+(r) = \begin{cases} w(r) \cdot \frac{H(r)}{q(r)} & \text{when } u(r) > \bar{u} \\ 0 & \text{when } u(r) \leq \bar{u} \end{cases} \tag{6.11}$$

and its aggregated sum over the whole city:

$$S_{rent} = \int_{u(r) > \bar{u}} m_{rent}^+(r) dr \tag{6.12}$$

To calculate the pressure on the housing market, we have to distribute, over the various locations, households who would like to move but cannot. We spread them over all attractive locations, in proportion to the number of dwellings at each place, we get:

$$n_{virtual}(r) = m_{rent}^+(r) \cdot \max(1, \frac{D - S}{S_{rent}}) \tag{6.13}$$

and then:

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[6]For instance in France, when there is no tenant change, rent can only change significantly every three years.

$$n^*(r) = n(r) + \max(\mu(r), 0) + m_{rent}^+(r) \cdot \max(1, \frac{D-S}{S_{rent}}) \qquad (6.14)$$

$n^*(r)$ can be different from the actual number of dwellings $\frac{H(r)}{q(r)}$. Anticipating that rents have an impact on dwelling size $q(r)$, but taking $n^*(r)$ and $H(r)$ as given, we can compute the rent $R^*(r)$ which adjusts dwelling size so that the number of dwellings becomes equal to $n^*(r)$:

$$R^*(r) = \beta \frac{(Y - T(r))}{H(r)} n^*(r) \qquad (6.15)$$

If a location is attractive, and more people want to live there, $R^*(r)$ will be bigger than $R(r)$. On the contrary, if some dwellings are empty, $R^*(r)$ will be lower than $R(r)$. We suppose that landowners vary their rents to set them equal to $R^*(r)$, with the timescale τ_R:

$$\frac{dR(r)}{dt} = \frac{R^*(r) - R(r)}{\tau_R} = \frac{1}{\tau_R} \left(\beta \frac{(Y - T(r))}{H(r)} n^*(r) - R(r) \right) \qquad (6.16)$$

6.A.5 Housing production function

Buildings depreciate, and are renewed or rebuilt by land owners in reaction to rental profitability. We suppose that some of them have a myopic behavior: they make investment decisions as if they were at a stationary state of equilibrium, and that some others make anticipations, and compares rents to rents that households would pay in an equilibrium state where all locations would have the same utility $\bar{u}$.

Housing $H'(r)$ is produced using land $L'(r)$ and capital $K'(r)$. The housing production function reads, in a classic way (Muth, 1969; Thorsnes, 1997):

$$H'(r) = AL'(r)^a K'(r)^b \qquad (6.17)$$

where A, a and b are coefficients ($a + b = 1$), $H'(r)$ the housing surface built, $L'(r)$ the ground surface occupied by the buildings and $K'(r)$ the financial capital used for construction. The benefit of land owners reads therefore:

$$\Pi(r) = (R(r) - R_0)H(r)' - \delta K(r)' \qquad (6.18)$$

$\Pi(r)$ is the profit, δ represents the joined effect of real estate capital depreciation, annual taxes payed by landowners on the real estate capital, and interest rate. Developers build to maximize their profit: at each point of the metropolitan area they construct, i.e. choose $K'(r)$, to maximize $\Pi(r)$ under the constraint that $\frac{H'(r)}{L'(r)}$ ratio is limited by an urbanism constraint (see detail in Section 5.1.2.2). The metropolitan area boundary is defined by a rent R_0, below which it is not profitable to build housing building (this value corresponds both to other use of the land like agriculture and to the transaction cost in the building and renting process).

As for the other equations that we have presented, let us reason per unit of land: because $a + b = 1$, we get

$$\frac{H'(r)}{L'(r)} = A \left(\frac{K'(r)}{L'(r)} \right)^b \qquad (6.19)$$

So if we define $H(r) = H'(r)/L'(r)$ and $K(r) = K'(r)/L'(r)$, we have:

$$H(r) = A(K(r))^b \qquad (6.20)$$

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Developers seek to maximize their profits. Some of them have a myopic behavior: they make investment decisions as if they were at a stationary state of equilibrium. This leads to the optimal capital:

$$K^*_{myopic}(r) = \arg\max_{K(r)}(H(r)R(r) - \delta K(r)) \tag{6.21}$$

$$= \arg\max_{K(r)}(A(K(r))^b R(r) - \delta K(r)) \tag{6.22}$$

Some city landowners make anticipations, and compares current rents to rents that households would pay in an equilibrium state where all would have the same utility $\bar{u}$:

$$R_{anticipate}(r) = \alpha^\alpha \beta^\beta \left(\frac{Y - T(r)}{\bar{u}}\right)^{\frac{1}{\beta}} \tag{6.23}$$

This leads to the optimal capital:

$$K^*_{anticipate}(r) = \arg\max_{K(r)}(A(K(r))^b R_{anticipate}(r) - \delta K(r)) \tag{6.24}$$

We suppose that half of the the land owners are myopic, and half make anticipations, which leads to an amount of capital:

$$K^*(r) = \frac{K^*_{myopic}(r) + K^*_{anticipate}(r)}{2} \tag{6.25}$$

Let us define $H^*(r) = A \cdot K^*(r)^b$ the corresponding optimal housing quantity.

Construction and building depreciation take time. We suppose that financial investments are transformed into buildings with a time lag τ_H, which corresponds to the time required to achieve the construction. We also suppose that a decrease in $H(r)$ can happen through depreciation only, with the timescale τ_{dH}. Housing quantity dynamics is therefore given by:

$$\frac{dH(r)}{dt} = \begin{cases} \frac{H^*(r) - H(r)}{\tau_H} = \frac{AK^*(r)^b - H(r)}{\tau_H} & \text{if } H^*(r) \geq H(r) \\ -\frac{H(r)}{\tau_{dH}} & \text{if } H^*(r) < H(r) \end{cases} \tag{6.26}$$

Part III

Applications: towards an assessment of adaptation and mitigation strategies

Chapter 7

The impact of a carbon tax on Paris metropolitan area and its population

This chapter is based on an article: "*The impact of a carbon tax on Paris metropolitan area and its population*" (Viguié and Hallegatte, 2011).

After decades of urban sprawl, many voices advocate for a densification or re-densification of cities. The usual arguments refer to reduced energy consumption, based for instance on the hardly-consensual results from Newman and Kenworthy (Newman and Kenworthy, 1989), and to improved health (see for instance Ewing et al., 2003; Eid et al., 2008) and quality of life (see for instance Brueckner and Largey, 2008). Here, we do not enter the debate surrounding the need or benefits from densification (on this debate, see Gordon and Richardson, 1997; Ewing, 1997). Instead of investigating why we should increase urban density, we focus on how to increase urban density and how much it would cost, assuming there is a political will to do so. A prerequisite to design density-increase policies is indeed to understand the cause of observed urban sprawl, and to explore various policy tools to curb it.

Different economic policy tools were shown to have a possible impact on urban density, from fiscal policy to land-use regulation. In the context of climate change mitigation, however, one often-discussed tool is a tax on transportation, through congestion toll, gasoline tax, or reduced transport speed (see for example Wheaton, 1974; Fujita, 1989; Brueckner, 1981). A specific form of transport tax is the carbon tax, and this approach has been regularly discussed in the public and policy debate in the last years, in particular in France. This article aims at informing public-policy decision-making on this issue.

We used NEDUM-2D-static (chapter 5) model to assess the impact of a 100 €/tCO$_2$ carbon tax on the urban area, and especially on its population densification. This tax level has been picked because it corresponds to the level recommended for 2030 by the French Government's Strategic Analysis Center (Quinet 2009). We analyze the tax impact over three timescales, all other things being equal: the immediate impact, the medium term impact after rents and household location have adjusted, and the long-term impact after the urban structure has adjusted. We find that the 100 / €CO$_2$ carbon tax would reduce by up to 10 % the average distance of households from the center of

Paris, but only over the long term. Over the medium term, i.e. from a few years to a few decades, this distance would only decrease by 2.5 %. Moreover, the tax has significant redistributive impacts on households and landowners, but these impacts vary with the considered timescale. The fact that a significant carbon tax has only moderate results on densification is not valid on Paris only, and can be transposed to other major cities facing same issues.

Section 7.1 explains the framework of this study, and main hypotheses of our computations. Section 7.2 presents results over the medium-term and Section 7.3 over the long-term. Our model is by nature a simplification of reality, so several precautions must be taken when one wants to draw practical conclusions from it. We discuss these caveats in Section 7.4.

7.1   Framework of the study

Carbon tax acts on households through different channels: heating price change, consumption goods price change, transport price change, etc. The transport price change itself is divided into different subcategories: commuting trips price, shopping trips price, etc. In the present analysis, we are only considering the impacts of commuting trips price change, and we take journeys towards downtown as a proxy of commuting trips. Indeed, it is assumed that commuting trips play a key role in the choice of households' location, even when such trips constitute only a limited fraction of their journeys.

Since commuting trips are taken here as journeys towards downtown, willingness to reduce the distance of these trips will be equivalent to a willingness to reduce the average distance of households to the center of Paris, and a reduction in these trips will correspond to a densification of the metropolitan area.

For simplicity, we suppose that all households are tenants, and that owners live outside the urban area. This assumption simply means that, when rents vary, we do not take into account the resulting variation of owners' income effects on the economy of the city. These effects can indeed be taken as second-order effects. We verify this assumption ex post by noting that, when rents vary in following computations, aggregated changes in owners' income are relatively low compared to overall aggregated owners' income.

We also assume that owners and real estate developers are the same people, i.e. there is no conflict of interest between real estate developers that determine the amount of available habitable surface and owners that determine the level of rents. A detailed examination of the consequences of this hypothesis is carried out at the beginning of Section 7.4 when we examine the inequalities created by the carbon tax among owners and developers.

In all that follows, we assume that the carbon tax is fully given back to households, and equally divided so that each household receives the same amount. We examine the effects of a 100 € per ton of carbon emission tax, i.e. a 18 eurocents/liter pump price tax. It is assumed that public transportation prices are increased in a similar way. We thus focus on redensification, not on modal shift, energy consumption and CO_2 emissions.

This tax creates an inequality between households: those living far from Paris center pay a higher charge (385 €/year for a household living 25 km from the center) than those living close to the center (who do not pay any tax if they live exactly in the center of Paris). This tax causes on average a 220 € increase in households annual transport

expenditures (it corresponds to 0.4% of total income), and this is the amount that is given back to each household, regardless of its location.

The inequality generated by the tax will cause a response of the various actors in the city (households, owners and real estate developers), each trying to improve its condition: households will move, owners will adjust rents, and real estate developers will change the built environment until the urban area reaches a new state of equilibrium, assuming that, after the introduction of the tax and the associated transport price change, transport price do not vary again. Responses of various actors will not however occur all at the same speed (here we follow the approach of Gusdorf and Hallegatte, 2007a,b). On the one hand, households' moving, rents change, and dwellings size change take place on a timescale of a few years, and on the other hand changes in the built environment occur on a much longer time scale (Mayer and Somerville, 2000). Hence, we analyze successively the state reached when only households and owners have responded and the built environment remains identical (the "medium term"); and secondly the state reached when changes in the built environment have taken place (the "long-term")[1].

7.2 Medium-term adjustments

Households living far from city center are hit harder by fuel price increase than those living close to city center, and therefore the former will try to move closer to downtown. This pressure will push downtown rents upwards. Because of the increase in rents, households living near downtown will tend on average to live in smaller flats, which will make room for a few people from the suburb. Conversely, to stop their tenants running away, the owners in the suburb will have to lower the rents, until suburb rents are low enough and downtown rents high enough so that living in the suburb will be attractive again. We find that this decrease is bigger than a simple compensation of transport costs increase, and flat sizes in the suburbs increase.

When a steady state is reached, rents as well as population density have therefore increased in the center and declined in the suburbs. Dwellings have become smaller in the center and have slightly increased in size in the suburbs. Quantitatively, households average distance to city center decreases by 1.5%, i.e. 250 m. If the available income after having paid housing, transport and receiving tax compensation do not vary much (there is a slight 0.35 € gain per year), the average size of dwellings decreases by 0.5% (40 cm²) due to city densification, and households utility decrease by 0.12%, i.e. 57 € per year in monetary equivalent.

This adjustment cancels the inequalities between tenants that the carbon tax introduction had caused. However, it creates inequalities among owners: whereas downtown owners rent increase (rents in the center of Paris increase for example by 2%), suburban owners rent decrease (rents 25 km from the center decrease for example by 0.5%). Suburban owners are therefore net losers over the medium term.

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[1]It must be noticed that, apart from the application of the carbon tax, we reason at constant fuel prices. It is likely that in reality fuel prices will significantly vary during the urban area adjustments, resulting in changes going in the same direction that we described if fuel prices increase, or in the opposite direction if fuel prices decrease. These effects will be added to carbon tax effects, and may even hide them it if they are too large.
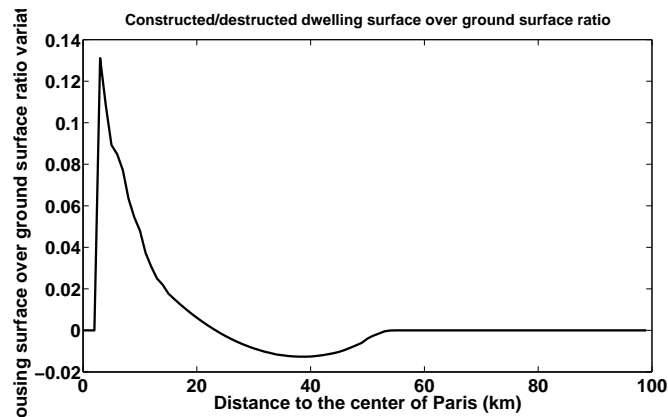
Figure 7.1: Built surface over ground surface ratio variation between medium term and long term

7.3 Long term adjustment

In the long run, the built environment adjusts: because of rent changes and households moving, it becomes profitable to construct more or higher buildings in the center of the urban area, while some suburban dwellings are not profitable any more. We can then assume that constructions and destructions of buildings occur so that owners/developers profits are maximized. It is therefore expected to find new dense and high buildings in the near suburbs, where additional building is allowed (in our model, because of constraint on the height of buildings, their adjustment cannot be done inside Paris). In the distant suburbs, old buildings are not renovated or replaced due to insufficient rents. This can be seen in Fig. 7.1, which shows built surface over ground surface ratio change between the initial and final situations.

In the end, the city is more concentrated than before: households average distance from city center is reduced by 10% (i.e. 1700m) compared to initial state without tax, i.e. reduced from approximately 17 km to 15.3 km. Annual housing rental income increases by 7.7% (in average 3.59€ per square meter) compared to the initial state. Compared to initial state, rents increase by 2.7% in average, i.e. 0.4 /€m^2/month, and average dwelling surface decreases by 2% (i.e. 1.7 m^2). As a result, utility is reduced by 0.3% (i.e. 140€ in monetary equivalent) in spite of the increase by 170€ (0.3% of the income) of household disposable income after paying tax, housing and transport.

It should be noticed that this adjustment corresponds to a net gain for owners/developers as a whole, i.e. to a transfer from tenants to owners/developers. Indeed, the medium term corresponds to a situation in which tenants have the flexibility to move while owners/developers have fixed properties. The long term allows the latter to adjust their properties, improving their situation at the expense of tenants (especially in far suburbs, in which housing over-capacity disappears over the long term).

Variation, compared to initial state :	Short-term			Medium-term			Long-term		
	Center	Weighted average[*]	25km from the center	Center	Weighted average[*]	25km from the center	Center	Weighted average[*]	25km from the center
of households average distance to city center	-	+ 0	-	-	-253 m	-	-	-1694 m	-
percentage		(+ 0%)			(-1.49%)			(-9.98%)	
of monthly rent ($/€m^2$)	+ 0	+ 0	+ 0	+ 0.48	+ 0.11	-0.07	+ 0.59	+ 0.41	-0.02
percentage	(+ 0%)	(+ 0%)	(+ 0%)	(+1.94%)	(+0.70%)	(-0.53%)	(+2.39%)	(+2.71%)	(-0.12%)
of dwelling size (m^2)	+ 0	+ 0	+ 0	-0.82	-0.41	+ 0.23	-1.09	-1.66	-0.18
percentage	(+ 0%)	(+ 0%)	(+ 0%)	(-1.45%)	(-0.50%)	(0.26%)	(-1.92%)	(-2.05%)	(-0.20%)
of households' disposable income ()€	+ 262.56	+ 0	-123.91	+ 181.05	+ 0.35	-89.48	+ 165.46	+ 168.99	-105.07
as a fraction of total income	(+0.47%)	(+ 0%)	(-0.22%)	(+0.32%)	(+0.00%)	(-0.16%)	(+0.29%)	(+0.30%)	(-0.19%)
of households' utility ()€[**]	+ 262.56	+ 0.00	-123.91	-	-56.27	-	-	-138.91	-
as a fraction of total income	(+0.47%)	(+ 0%)	(-0.22%)		(-0.10 %)			(-0.25 %)	
of annual owners' rental income per square meter ($/€m^2$)[***]	+ 0	+ 0	+ 0	+ 5.78	+ 0.66	-0.83	+ 7.12	+ 3.59	-0.71
percentage	(+ 0 %)	(+ 0 %)	(+ 0 %)	(+3.49%)	(+1.43%)	(-3.32%)	(+4.30%)	(+7.74%)	(-2.81%)

[*] It is an average between all households (or, equivalently, it is an average between all locations weighted by the number of households). Since households are moving during the adjustments, it does not correspond to a fixed location. For instance, dwelling size variation in the long-term is bigger averaged between all households, than computed at any given location.

[**] The change in utility is expressed in monetary terms : it is the variation of composite good needed to obtain the same variation in utility. In the short-term, for instance, it is strictly equal to the composite good variation.

[***] Owner's rental income is equal to rent minus charges (11 $/€m^2$/month cf Chapter 5).

Table 7.1: 100 €/tCO$_2$ carbon tax impacts on Paris urban area, when no adjustment has taken place ("short term"), when households have moved and rents changed ("medium term"), and when built environment has also adjusted ("long term"), compared to the initial state

Ground owners' income after building adjustment, as a fraction od initial ground owners' income
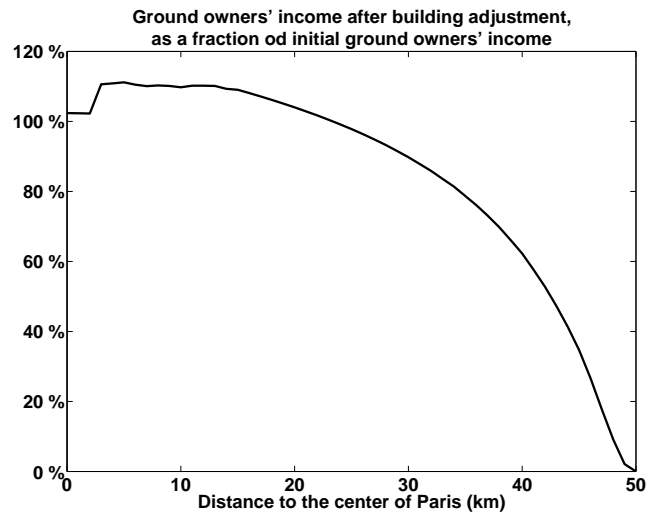
Figure 7.2: Owners/developers rental income variation between medium term and long term

7.4 Practical conclusions for Paris and more generic lessons

Our simulations compute that the 100 €/tCO$_2$ carbon tax would reduce by by 2.5 % the average distance of households from the center of Paris over the medium term, i.e. from a few years to a few decades, and by up to 10 % over the long term.

What can we conclude from these results? First, it is possible to wonder about the practical feasibility of the passage from the "medium" to the "long term". Indeed, if this passage is optimal at the aggregate level, and creates a net gain for owners/developers as a whole, actual profit actually depends on owned property location. For example, as illustrated in Fig. 7.2, downtown owners' rental revenue increases to 102.4% of its initial value, compared to 97.8% (i.e. a loss of 2.2%) for owners of buildings located at 25 km from the center. Optimal adjustment needs suburban owners to reduce the dwelling surface they rent, which makes them lose income. This outcome may thus appear unlikely, as already observed in shrinking cities (Reckien, 2007). This difficulty may be lifted in the case of a growing city: indeed in this case it is possible to see the reduced housing area not as an absolute decrease, but as a relative decline compared to the rest of the city. This is a slower development instead of a net reduction, which poses fewer problems of acceptability. A generic lesson from this exercise is thus that it is much easier to influence the development of a growing city than to modify a city with stable population. This is an incentive to act rapidly in developping countries, where most wities are rapidly growing.

These problems suggest that the decrease in Paris average radius will not be 10% as computed for long term equilibrium, but will rather be between 1.5% for the medium term equilibrium and 10% for the long term.

Secondly, the technological changes that carbon tax may induce, such as the production of electric vehicles or the development of more efficient vehicles, will also limit households sensitivity to the fuel price increase. As already mentioned, we do not model modal shift, and assume that both public and individual transport prices increase in parallel, with the aim of increasing urban density. A differentiated price policy for

Average urban radius variation because of the tax, as a function of the number of households
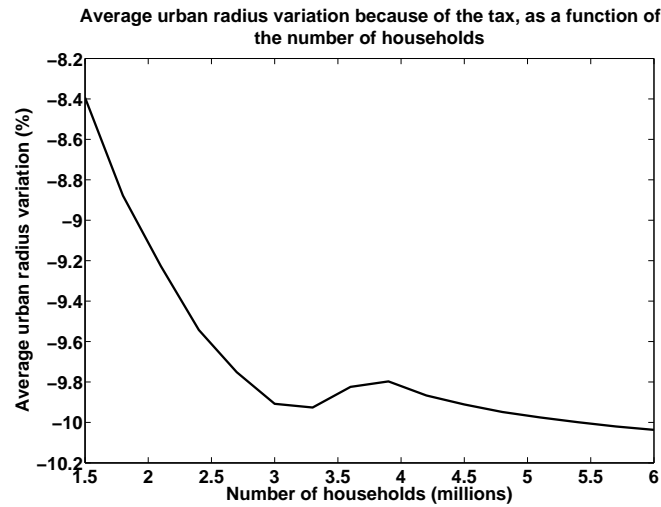
Figure 7.3: City densification caused by the tax, as a function of city population (in previous simulations, there were 5,100,000 households)

these two modes could influence results (see for instance, Berg (2007), and Schmutzler (2010), for modeled and empirical results on the effect of carbon tax and transport tax on modal shift and greenhouse gases emissions).

Our model is a monocentric modeling of Paris urban area, whereas more and more studies now recommend polycentric framework to describe cities. It is interesting to observe that a monocentric model is however able to reproduce the main characteristics of the Paris urban area, when averaged as a function of the distance to the center of Paris. Here, a polycentric approach would mean assuming that, under the effect of the tax, households will not move closer to the center of Paris, but rather closer to secondary centers of the urban area. Part of the households would therefore move towards Paris and the others towards several different secondary centers. For each of these centers the framework of the present study remains valid, as long as for each center we restrict the computation to the households who depend directly on it. Therefore, it is possible to take into account the possibility of a polycentric development simply by using the model again, but several times on different centers, where each one will have a population which is a fraction of the total Paris urban area population. But, as computed by our model, the bigger the total population of the city, the bigger the densification caused by the carbon tax (Fig. 7.3). Hence, a polycentric response of the urban area would lead to a set of densifications all below the 10% of the monocentric case, resulting in an overall lower total densification.

Finally, we can therefore estimate that our computation corresponds to an ideal case, which is rather optimistic. Even in this case, this reduction is not very high (1700 m), so our calculation suggests that in practice a carbon tax of 100 €/tCO$_2$ will produce a limited effect on the densification of the metropolitan area. A 100 € tax seems already quite difficult to be accepted in France, so our calculations encourage us to think that a transport tax is not sufficient to get a denser Paris urban area, and must be combined with other measures (see for instance Banzhaf and Lavery, 2010b) if ones wants to achieve this objective. This conclusion, here reached on the specific case of Paris, would remain valid in other urban area. A carbon tax -even with a significant

level- would be unable to influence urban densities in a significant manner. If urban (re)densification is a policy goal, other tools will need to be used, including land-use regulation and taxes, or direct investments in transport or service infrastructure.

Two important limits of the analysis we have done are related to the fact that we have not taken into account actual city evolution dynamics. First, it is possible to wonder about what are exactly short-term, medium-term and long-term, and how much time will be required to reach them. This issue will be addressed in Chapter 8, by using the dynamical model we have described in Chapter 6.

Second, no city evolution was taken into account (population, transport technology, economy...), therefore limiting our conclusions. To address this issue, we need to base our analysis on prospective evolution scenarios of these variables. This issue will also be addressed in Chapter 6.

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Chapter 8

Downscaling long term socio-economic scenarios at city scale

This chapter is based on an article: "*Downscaling long term socio-economic scenarios at city scale: a case study on Paris*" (Viguié et al., 2011).

This Chapter is in the continuity of Chapter 7, and uses the dynamical version of NEDUM-2D to quantify evolution timescales. It goes further by introducing in the analysis the idea of prospective scenarios, which are required to take into account uncertainty on future city evolutions.

The NEDUM-2D model is used to downscale 32 global socio-economic scenarios at a city scale and simulate the evolution of the Paris urban area between 1900 and 2100. Four technico-economic, 2 demographic and four local scenarios are used as inputs to explore various possible future evolutions. Main drivers of urban sprawl and climate and flood vulnerability appear to be demographic growth and local policies; energy and transport prices, even including possible peak-oil and carbon taxes, have only a limited influence on them when assuming prolonged economic growth. Conversely, transport-related greenhouse gases emissions are mainly driven by vehicle efficiency changes. These scenarios are a useful input for the design and assessment of mitigation and adaptation policies.

Several conclusions can be drawn from the simulations. Concerning climate change mitigation, the main conclusion is that urban sprawl seems to be only moderately affected by technico-economic considerations: main drivers appear to be demographic growth, and local policies (urban planning, local taxes, and investment in transport infrastructures). Energy and transport prices, even including possible peak-oil and carbon taxes, have only a limited influence on them when assuming prolonged economic growth. Conversely, transport-related greenhouse gases emissions are mainly driven by vehicle efficiency changes.

Concerning climate change adaptation, flood exposure increases with overall urbanized area extension, through an increase in inhabited flooding-prone areas. On the other hand a decrease in population density, cuts on the flooding exposure because population living in each flooding-prone area diminishes. The overall outcome depends heavily on demographic scenarios and local policies, as is the case for mitigation is-
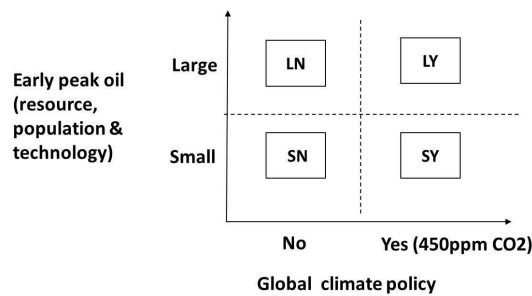
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Figure 8.1: Techno-economic scenarios

sues. Heat wave vulnerability might be increased, through an increased urban heat island effect caused by urban extension; increase in the artificialized area might also lead to an increase in floods' intensity, if no appropriate policy is carried out.

Section 8.1 describes the hypotheses that have been used in our scenarios. Section 8.2 investigates the results of our simulations, and draw general conclusions regarding climate change mitigation and adaptation. Finally, section 8.3 concludes.

8.1 Scenario hypotheses

Our aim here is to illustrate how NEDUM-2D can be used to downscale global scenarios. Therefore, we use a simple example of global scenarios. Such an exercise has no claim to predict the future: its goal is only to help structure thinking about some important determinants of urban structure evolution and identify the potential orders of magnitude of their impacts.

8.1.1 World evolution scenarios

We use a set of four contrasted scenarios on world evolutions, based on several hypotheses on world population growth, fossil fuel reserves, technology availability and climate policies (Figure 8.1). These hypotheses are used as input by Imaclim-R model (Rozenberg et al., 2010) to compute coherent quantitative techno-economic scenarios on income, transport prices and technologies over the 2010-2100 period.

Imaclim-R is a global hybrid general equilibrium model with endogeneous technical change. It represents the world economy, disaggregated into 12 regions and 12 sectors. The model is hybrid in the sense that it combines macroeconomic consistency with technology explicitness. Moreover, this framework encompasses second best features: the possible underutilization of production factors (labour and capital), the interplay between technological inertia and imperfect foresight (the price signals incorporated in adaptive expectations is a function of current prices and past trends), and the rigidities of labor markets. It simulates for instance energy prices, technology market penetrations, energy production, and transport technology prices.

Main determinants of these variables include future fossil fuel availability and future climate policies. The four scenarios were computed by combining (1) two assumptions on future tensions on fossil fuel markets and (2) two assumptions on future world climate policies (see a detailed presentation of the model and of the scenarios in

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Rozenberg et al., 2010; these two worlds are part of the 576 worlds designed for this article).

Assumptions on future tensions on fossil fuel markets result from a combinaison of hypothesis on exogenous parameters of the model describing natural resources, technologies and international economic trends. They include parameters describing oil and gas markets, the Middle-East strategy, coal markets, the availability of alternative liquid fuel supply, carbon free options for power generation and end-use technologies, and development patterns.

These parameters have been combined to maximize the difference in energy and transport prices in 2050 in these two worlds. In scenarios LN and LY (cf. Fig. 8.1), fossil fuels are largely available until 2040 (for instance the amount of ultimately recoverable oil resources is 3.6 Tb) while demand is high and locked in carbon-intensive pathways (development pathways are energy-intensive and the potential for low-carbon technologies is low; for instance electric vehicles cannot significantly penetrate the market). In scenarios SN and SY, the peak oil happens before 2030 (the amount of ultimately recoverable oil resources is 3.1 Tb) while the potential for low-carbon technologies is high (e.g. electric vehicles can penetrate the market as soon as 2010) and demand is less carbon-intensive. 8.A gives a full description of all parameters values used in these two assumptions.

For climate policies, the model simulates either (i) a "Business As Usual" (BAU) world with no constraint on emissions (scenarios SN and LN), or (ii) a "stabilization" world in which a global carbon price reduces emissions such that CO_2 concentration is stabilized at 450 ppm in the long run (corresponding to a 550 ppm CO_2eq. stabilization)(scenarios LY and SY).

Figure 8.3 shows some variables of the resulting techno-economic scenarios, and Fig. 8.2 shows the associated oil prices and carbon tax[1]. Imaclim-R computes the evolution of vehicles usage costs. In our scenarios, we suppose that public transport prices evolve proportionally to public transport usage cost, i.e. that the fraction of subsidy in public transport cost remains constant.

In the Imaclim-R model the oil price is endogenous. As the model is calibrated on the 2001 GTAP database and disregards some of the mechanisms driving market oil price (especially geopolitical tensions, the impact of changes in exchange rates, and market speculation), the steep increase of oil prices which happened before 2008 is not reproduced, and the oil price remains around 80$/bl until 2015 (see Fig. 8.2(a)).

In techno-economic scenarios LN and LY, fossil fuels are largely available until 2040, and there is a limited potential for low-carbon technologies. The large availability of oil maintains low prices for the first thirteen years of the projected period. Then, a steep twenty-year-long surge in oil prices begins just before oil production starts to decrease (i.e., before the peak oil; see Fig. 8.2(a)) and brings the oil price up to 450$/bl. This surge is triggered by a tension between high demand, which cannot be reduced overnight, and constraints on the deployment of oil substitutes (e.g. vehicles electrification). This is the logical outcome of a small potential for low-carbon technologies combined with low energy prices in the first period. These low prices (a) induce intensive energy consumption, (b) cause faster exhaustion and a sharper decline of conventional oil, and (c) deter investment in non-conventional production capacities and limit their availability in the post-Peak Oil period. From 2040 on, the surge in oil prices is sufficient to trigger energy efficiency and technical change towards low-carbon

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[1]Oil prices and carbon tax are not directly used as inputs by NEDUM-2D. Only transport prices for individual car and public transport (Fig. 8.3(a) and 8.3(b)), income evolution (Fig. 8.3(c)) and average vehicle fuel consumption (Fig. 8.10(d)) are used in our simulations.

(a) Oil price (excluding carbon tax).   (b) Carbon tax in scenarios SY and LY.
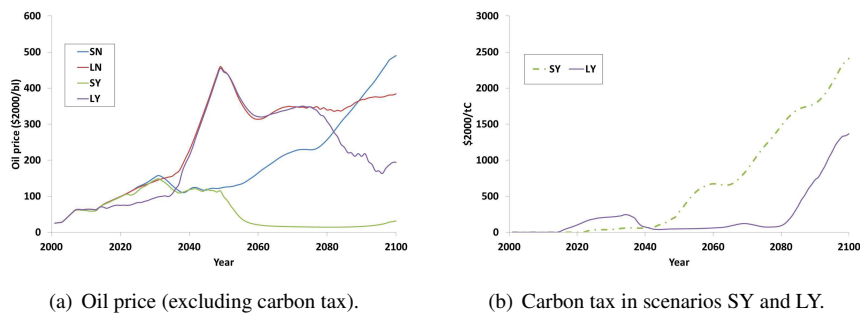
Figure 8.2: Oil price and carbon tax computed by Imaclim-R model in the four scenarios. The carbon tax is applied everywhere around the world, and is computed so that CO_2 concentration is stabilized at 450 ppm in the long run (corresponding to a 550 ppm CO_2eq. stabilization). There is no carbon tax in Techno-economic scenarios SN and LN.

technologies, so that oil demand starts declining and the oil price goes back down to around 350$/bl. In scenario LY, this technical change is sufficient to meet the climate target with a relatively low carbon tax until 2080. After 2080 though, the climate target becomes more stringent and the carbon tax has to increase steeply so as to tackle the most inert sectors of the Imaclim-R model (see Fig. 8.2(b)). As a consequence, the oil price drops to about 200$/bl because oil demand decreases in the transportation sector.

The steep increase in oil price between 2040 and 2080, in scenarios LN and LY, is translated into the cost of private vehicles transport and public transport (see Fig. 8.3), but to a lesser extent. This is due to a rapid turnover in the stock of private vehicles, which can be replaced in ten years by more efficient vehicles and hybrids, and to the fact that public transports include a large part of electric technologies.

In techno-economic scenarios SN and SY, a weak Peak oil happens before 2030 and the potential for low-carbon technologies is high. In that case, oil demand is lower in the short-run than in scenarios LN and LY, preventing a strong peak oil in the 2040's. But from 2040 on, oil price increases continuously in scenario SN, until it reaches 500$/bl in 2100 (see Fig. 8.2(a)). This regular increase is due to the decrease in oil production, combined with high potential for technical change towards low-carbon technologies. This high potential prevents the economies from being locked in very oil-intensive technologies (as in scenario LN), so that there is no surge in oil price when Peak Oil is reached. However this regular increase in oil price is not sufficient to meet the climate target, so in scenario SY the carbon tax rises sharply to tackle the most inert sectors of the model (see Fig. 8.2(b)). As a consequence of this high carbon price, the oil price falls below 50$/bl after 2060 in this scenario.

The high potential for decarbonisation in the scenarios SN and SY (e.g. in terms of electrification of vehicles) is translated into constant costs for private and public transportation in scenario SN, and a decreasing cost in scenario SY (see Fig. 8.3). This decreasing cost is due to a high penetration of electric vehicles in the park, as well as electricity decarbonisation, which are triggered by the carbon tax sharp and regular increase.

8.1.2 Local scenarios

These global inputs are not sufficient to create local-scale scenarios, which depend on many other factors. In particular, several local inputs are also needed.
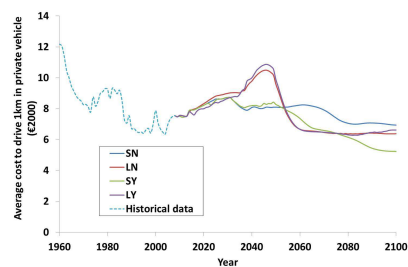
(a) Average cost to drive 1km in private vehicle, including electric vehicles and carbon tax (Source for historical data: F. Nadaud (Nadaud and Hourcade, 2009), after CPDP)
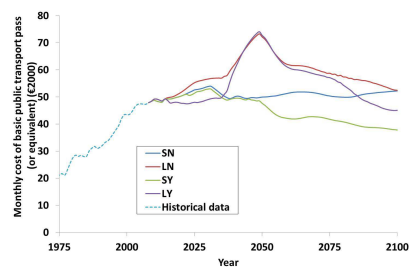
(b) Monthly cost of basic public transport pass (or equivalent), including carbon tax (Source for historical data: F. Nadaud (Nadaud and Hourcade, 2009), after RATP)
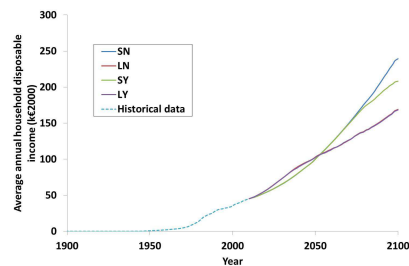
(c) Average annual household disposable income. The curves for scenarios SY and LY are almost identical. Source for historical data: J. Friggit, CGEDD after INSEE[*].

Figure 8.3: Example of inputs from Imaclim-R model. Scenarios SN and SY represent a world with high resilience against fossil fuel tensions. Scenarios LN and LY represent a world with high peak oil, happening in 2040. Scenarios SN and LN represent a world without any global climatic policy, contrary to scenarios LY and SY.

[*]Series downloadable on

www.cgedd.developpement-durable.gouv.fr/rubrique.php3?idrubrique=138.

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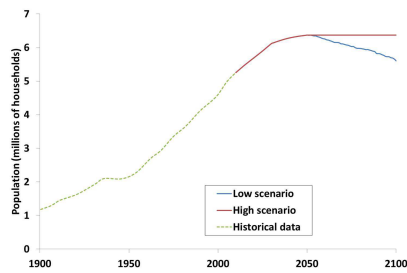
Figure 8.4: Demographic scenarios. Source for historical data: INSEE.

Paris urban area population evolution and households size   As inputs for population evolution and households size, we used two demographic scenarios (Fig. 8.4). The Low one is based, for the 2010-2030 period, on a scenario produced by the French national statistical institute (INSEE) and by the urbanism institute of Ile de France (IAU) for Paris urban area (Louchart, 2010b). For the 2030-2050 period, it is based on a scenario produced by INSEE for France (Robert-Bobée, 2006), and for the 2050-2100 period by a scenario produced by the UN for Europe (UNPD, 2011). The High scenario is the same as the Low scenario until 2050, and is then constant.

Development of transport infrastructure   Many different assumptions about the future development of transport infrastructure can be tested with the model. For simplicity, we suppose here that infrastructure pattern remains unchanged between 2010 and 2100, and that congestion on roads and public transport remains at current levels, i.e. future investments in the transportation network are assumed to maintain the same service level in spite of population growth, without developing new lines.

Urbanism policies   We use four different scenarios for local urban policies. In the first one, we suppose that the extension of the city is entirely guided by the market: we introduce no policy or regulation limiting the extension of the city or preferentially developing certain areas. The idea is to study the "natural" trend of development of the city; this trend does not necessarily match the development that will occur in practice, but it allows understanding and anticipating land pressures, and therefore future local challenges.

In the second one, we suppose that an efficient "Green Belt policy" is enacted in 2020 to control urban sprawl and protect natural areas and agriculture activity. From that year on, building is only possible through a densification of existing built spaces, but is prohibited elsewhere.

In the third one, we suppose that a zoning policy to reduce the risk of flooding is implemented in 2020. This policy prohibits new constructions in flood-prone areas, but do not act on existing buildings.

Finally, in the fourth one, we suppose that both a flood-risk zoning policy and a green-belt policy are implemented together, in a policy that combines adaptation and mitigation objectives.
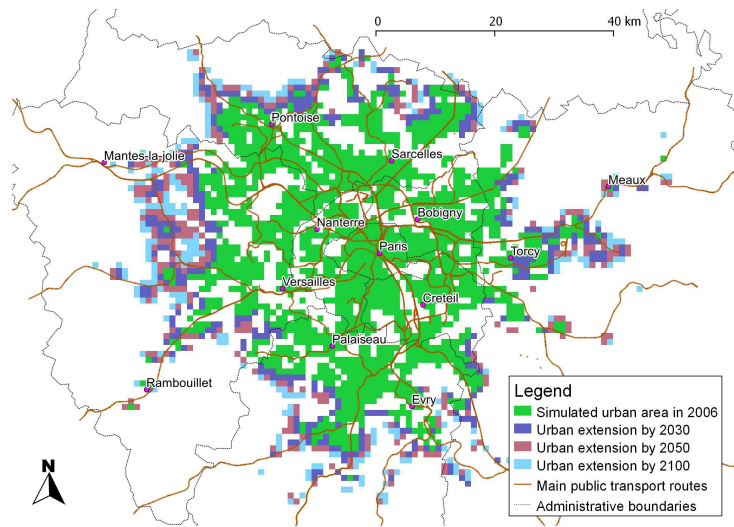
Figure 8.5: Example of simulated urban area extension, using techno-economic scenario 1 and high demographic scenario.

8.2 Results

Model results can be analyzed in view of three policy goals: reducing urban sprawl, mitigating climate change, and adapting to it.

8.2.1 Urban sprawl

Figure 8.5 presents an example of projected Paris urban area extension between 2010 and 2100. This example corresponds to a techno-economic scenario with a limited and early peak oil, no global climate policy to curb world greenhouse gas emissions (techno-economic scenario SN) and a demographic scenario where Paris urban area population grows until 2050, and then remains constant (high demographic scenario). In this scenario, Paris urban area expands greatly, especially between 2010 and 2030.

Changing these hypotheses changes the simulated expansion, but all factors do not have the same impact. Figure 8.6 shows a simulation with the same techno-economic hypotheses, but with a decreasing population between 2050 and 2100 (the low demographic scenario). In this case, some urban locations are abandonned (which could lead to city management problems, as observed for instance in eastern european shrinking cities, see Bontje (2005)). However, other locations continue to be developed between 2050 and 2100, in spite of the decrease in population. This is due to the decrease in transport costs relative to income, and the subsequent population density decrease.

Techno-economic considerations seem to affect only moderately urban sprawl when compared with the impact of urbanism policies, and population changes (see Fig. 8.7). Even the presence of a carbon tax (at the value needed to stabilize CO_2 concentration at 450 ppm, i.e. about \$1000) does not influence significantly urban sprawl.

This result has two origins. Firstly, it is caused by our world scenarios: in these scenarios, an important "peak oil" and a high carbon tax impact moderately transport prices (the maximum increase is about 20%), because they are compensated by vehicle energy consumption decrease and alternative energy use (especially electric vehicles

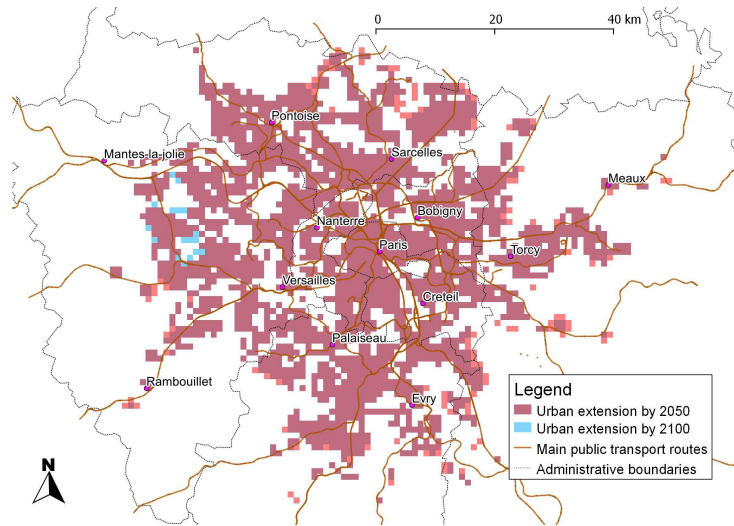Figure 8.6: Example of simulated urban area extension, using techno-economic scenario 1 and low demographic scenario.
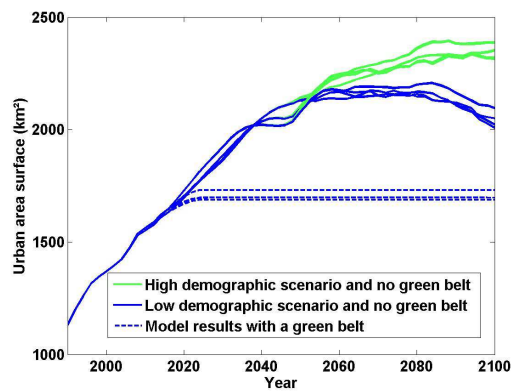

Figure 8.7: Urban area extension as simulated by NEDUM-2D. Plain green curves correspond to scenarios with a high population, and blue ones to scenarios with low population, with no green belt policy in both cases. The dashed curve correspond to scenarios with the green belt policy.

and decarbonized electricity in the case of scenarios with a climate policy and liquefied coal in the other scenarios).

Secondly, in our model, households respond to a generalized cost of transport, which is the sum of the actual monetary cost of transportation, plus a cost associated to travel time. To compute the latter, as explained in Section 5.2, we use a cost of time which increases proportionally to households income. In all the simulations computed by the Imaclim-R model, households income increases strongly (almost exponentially) over time (Fig. 8.3(c)), whereas transport monetary cost increases only moderately (Fig. 8.3(a) and 8.3(b)). Therefore, in all scenarios, transport monetary cost becomes gradually negligible compared to transport time cost (Tab. 8.1). As transportation times are the same in all our scenarios, the differences between scenarios tend to decrease.

Year	2010	2050	2100
Monetary cost ($€2000$)	1,070	1,210	1,150
Fraction of generalized cost	*9.79%*	*5.31%*	*2.15%*
Time cost cost ($€2000$)	9,870	21,580	52,240
Fraction of generalized cost	*90.21%*	*94.69%*	*97.85%*

Table 8.1: Comparison between transport monetary cost and cost associated to transport time, in average, 20km from the center of Paris. Cost associated to transport time appears to be about 10 times higher than transport monetary cost in 2010. This ratio increases over time.

As highlighted in Section 6.2.1 in Chapter 6, there are some empirical and theoretical evidences that time cost may not evolve proportionally to income , because of technological innovations that make travel more comfortable.[2] The elasticity of time cost relative to income variation may be as low as 0.5 (Shires and de Jong, 2009). But it should be noted that, even in this case, in the simulations, costs associated with transportation times increase much more over the century than monetary transport costs, and that urban sprawl remains marginally impacted by energy prices.

This result suggests especially that climate policies based on a carbon price aiming at limiting global emissions[3] would only have a marginal impact on urban shapes: other policies are needed to slow down urban sprawl. Examples of these policies include specific land-use policies (urban planning regulations such as the green belt policy modelled here, but also other policies such as local taxes), or direct investments in transport which would change travel times across the urban area. This result is consistent with Chapter 7, which concluded that a $100€/tCO_2$ carbon tax alone seemed unsufficient to mitigate urban sprawl.

Of course, techno-economic scenarios with a lower income growth, or even with an income stagnation or decrease could lead to different conclusions.

8.2.2 Mitigation

All scenarios predict a growth in dwelling size, coherent with historical trends (Fig. 8.8). This growth appears to be mainly impacted by the existence or not of a greenbelt

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[2]It may also seem reasonable to imagine a scenario where an increasing transport congestion would make travel less comfortable. In such a scenario, time cost would increase more rapidly than income.

[3]In the techno-economic scenario 3, the tax increases constantly over time reaches 2500 $/tC in 2100, and in techno-economic scenario 4 it reaches 2500 $/tC in 2100.

policy: when such a policy is implemented, increased land scarcity leads to an increase in real estate prices, and hence to smaller dwellings[4]. However, in all scenarios, transport cost decreases relatively to income. This enables people to locate more and more uniformly in the urban area (cf. box in Section 4.1.2 in Chapter 4), thus reducing real estate pressure, and counterbalancing the former mechanism. Consequently, even when a greenbelt policy is implemented, dwelling size appears to increase over time (although less quickly than when no green belt policy is implemented). Such an increase could have an impact on greenhouse gases emissions, through an increase in energy consumption for heating or cooling.

The green belt enables also to mitigate public transport modal share decrease (Fig. 8.9). However, it does not appear sufficient to prevent this decrease, which happens for all scenarios.

As shown in Fig. 8.10, if transport-related emissions are impacted by many variables, the main influence comes from techno-economic scenarios, i.e. fuel prices and transport technologies evolution. The average distance traveled using private car (strongly related in our modelling to city sprawl) is greatly impacted by the implementation of a greenbelt policy, because of a modal shift towards public transport[5], and because of the reduced length of trips. However, in terms of greenhouse gases emissions, this has a much lower effect that the variation in vehicle efficiency and technology from the socio-economic scenario (e.g. availability of electric vehicles and decarbonized electricity).

In our downscaled scenarios, therefore, transport-related greenhouse gas emissions in the city are mainly driven by technologies. With the urban policies we have tested, urban planning plays a limited role in spite of its influence on the distance traveled by car. It means that if technologies cannot contribute to emission reductions, then limiting emissions from urban transportation would require the implementation of urban planning options that are much stricter than what has been investigated in this article. In practice, since a green belft would not be sufficient, it means that *urban reconstruction*, i.e. a combination of building destruction and construction, would become necessary.

8.2.3 Adaptation

These scenarios are also useful for impact, adaptation and vulnerability analyzes. In Paris, one of the main disaster risks is flooding, and climate change may increase this risk, even though models still disagree. Fig. 8.11 shows how population living in flood-prone areas[6] can be expected to evolve in the future. This data is an essential input to assess how changes in rainfall may translate into flood losses, and therefore to assess climate change impacts. The simulated population living in flood-prone areas is consistent with observations (empirical estimations for 1999 and 2006 are represented on Fig. 8.11). In all scenarios, this population increases until 2030 before decreasing slowly. This decrease is related to a diminishing population density in risk zones.

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[4]In practice, this could also lead to a reduced city attractivity, and therefore to a smaller population than in the scenarios with no greenbelt policy (in the line of Glaeser and Kahn, 2010). This could indirectly impact average dwelling size. In our simulations, demographic scenarios are exogeneous, so we could not study such phenomena.

[5]The densification of the urban area makes a larger fraction of the inhabitants live close to public transport stations.

[6]We used present-day flood-prone areas (Source: CARTO RISQUE, French Ministry of environment MEDDTL). This analysis could be made more refined by coupling the urban model with an hydrological model to take into account the impacts of climate change on the frequency and intensity of floods.
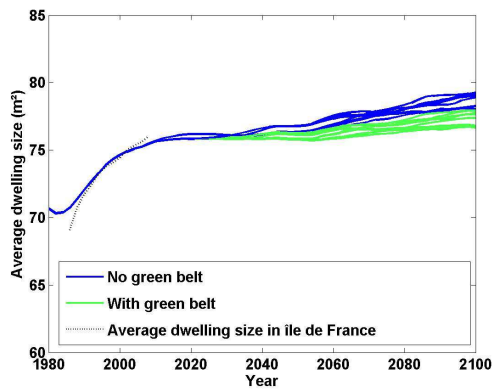
Figure 8.8: Average dwelling size evolution. Green curves correspond to scenarios with a high population, and blue ones to scenarios with low population. The dotted black line corresponds to actual historic data (Source : INSEE and IAU).
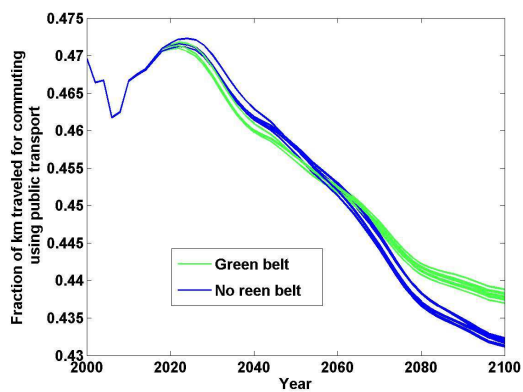
Figure 8.9: Public transport modal share for commuting trips. Actual data for 2002 is 46.63 % (Source : DREIF).

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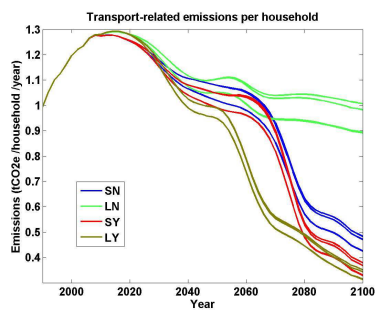
(a) Private car transport-related emissions per household

(b) Total private car transport-related emissions

(c) Average yearly distance traveled using private car, per household
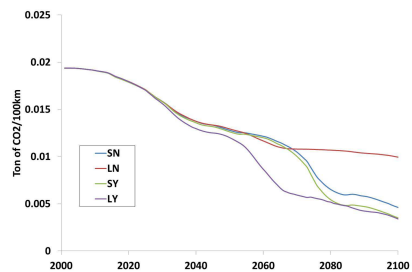
(d) Average vehicle fuel consumption. Average over all circulating private cars.

Figure 8.10: Private car transport-related emissions
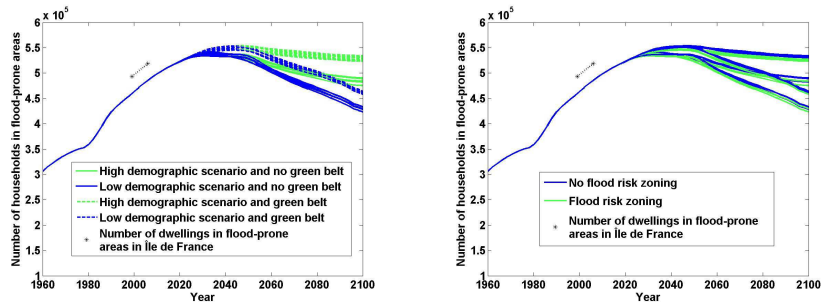
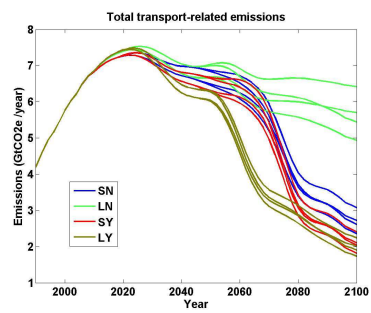(a) Green curves correspond to scenarios with a high population, and blue ones to scenarios with low population. Dotted lines correspond to scenarios with no green belt policy, and plain ones to scenarios with a green belt policy.

(b) Green curves correspond to scenarios with flood risk zoning, and blue ones to scenarios without.

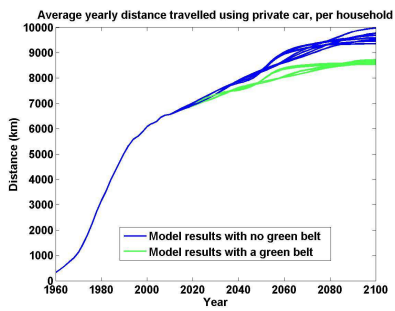Figure 8.11: Number of households living in flood-prone areas, as simulated by NEDUM-2D. The dotted black line corresponds to actual historic data (Source: French Ministry of environment MEDDTL (CGDD/SOeS), after Corine Land Cover and CARTO RISQUE databases).

It should be noted that a greenbelt policy appears to increase the number of households living in flood-prone areas (Fig. 8.11(a)), because it increases the population density of the urban area. Such a phenomenon has been observed empirically (Burby et al., 2001; Lall and Deichmann, 2010). This negative side-effect should be balanced with the positive effect on urban sprawl and transport demand (cf. Chapter 9 for a more detailed study of this idea).

This conclusion is true even when a flood-risk zoning is implemented (Fig. 8.11(b)): even when new buildings in flood-exposed zones are forbidden, more people are living in these zones when a greenbelt policy is implemented, because, as explained in section 8.2.2 dwelling size is smaller in these scenarios.

Heat wave vulnerability is another important topic strongly related to urban extension. To investigate this topic, three on-going research projects[7] are coupling this urban model with the urban microclimate model TEB (Masson, 2000b).

8.3 Conclusion

NEDUM-2D seems to capture main long-term determinants of city evolution: it is able to reproduce main tendencies of past Paris urban area evolution. It enables to derive scenarios for its long-term future. These scenarios appear useful to help decision-making about emissions reduction policies and climate change adaptation. Such an exercise do not predict the future: its goal is only to help structure thinking about some important determinants of urban trajectory and identify the potential orders of magnitude of their impacts.

The main conclusions of this study are not the quantitative figures computed in the scenarios, but the relative orders of magnitude and the qualitative reason explaining them. Firstly, transport price considerations seem to affect only moderately urban sprawl when compared with the impact of population changes and urbanism policies.

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[7]VURCA, MUSCADE and ACCLIMAT projects (http://www.cnrm.meteo.fr/ville.climat/?lang=en).

Even the presence of a carbon tax (at the value needed to stabilize CO_2 concentration at 450 ppm) does not influence it significantly. In other words, possible future fossil fuel prices increase seems not sufficient to slow suburbanization, and other measures are needed if one wants to slow down urban sprawl. Examples of these measures include specific land-use policies (urban planning regulations as has been , local taxes), or direct investments in transport.

The reason behind that is double: first, an important "peak oil" and a high carbon tax appear to impact moderately transport prices because of vehicle energy consumption decrease and alternative energy use. Second, and independently from this first reason, the importance on household location of transport prices decrease gradually relatively to the importance of transport times. This is due to the monetary value of time increasing similarly to the income, hence with a quasi-exponential trend due to the economic growth, whereas transport prices increase much more slowly, if at all. Such a phenomenon could be expected in every country where commuting transport times make up already the main part of commuting generalized transport cost.

A second conclusion is that, conversely, techno-economic scenarios play the major role concerning commuting transport-related greenhouse gases emissions. The reason behind that is, that, in all scenarios, the variation in transport demand, when demography changes or when a green belt policy is implemented appears to be smaller than the expected variation in transport efficiency. Only a much stricter anti-sprawl urbanism policy or much more contrasted demographic scenarios would ultimately be able to change this conclusion. The third conclusion is about climate change adaptation: concerning flood-risk, population living in flood-prone areas can be expected to evolve in the future. In all scenarios, this population increases until 2030 before decreasing slowly. This decrease is related to a diminishing population density in risk zones. A greenbelt policy appears to increase the number of households living in flood-prone areas, because it increases the population density of the urban area. This is true even when a flood-risk zoning is implemented: even when building in flood-exposed zones is forbidden, more people are living in these zones when a green belt policy is implemented, because, dwelling size is smaller in these scenarios.

Techno-economic scenarios with a lower income growth, or even with an income stagnation or decrease would lead to different conclusions. We have only downscaled in this study a small number of scenarios : to assess the robustness of the former results, other scenarios should be downscaled.

As our modeling is monocentric, it was not possible to simulate the effect of an increased development of other subcenters in the urban area. Such a development would greatly change travel patterns and the urban form, resulting in alternative scenarios. This is the subject of our present research. However, the mechanisms leading to the main conclusions of this paper do not depend on the city being monocentric or not, and should remain valid in the new model. A more complex, polycentric model will be useful to test the influence of other new variables, and especially investment in services supply (schools, health, leisure...) across the urban area.

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Appendix 8.A   The IMACLIM-R parameters

			Assumption 1	Assumption 2
Oil and gas markets	**Oil**	**Amount of ultimately recoverable resources (total conventional and non conventional)**[***]	3.6 Tb	3.1Tb
		Inertia in the deployment of non conventionals (spread of the bell-shaped curve for each field)	no inertia (b=0.061)	inertia (b=0.041)
		Maximum growth rate of Middle-East capacities	0.8Mbd/year	0.7Mbd/year
		Remaining resources before depletion starts	25%	50%
	Gas	Indexation of gas price on oil price	Until 80$/bl	Always indexed
OPEC behavior		Target oil price	40$/bl	80$/bl
Coal		Price growth elasticity to production decrease	1.5	1
		Price growth elasticity to production increase	1	4
		Production growth rate which cancels out price growth rate	2%	0,05%
Power generation decarbonization	**Nuclear**	**Maximum market shares [min - max]**[**]	[2.5% - 20%]	[5% - 40%]
	Renewables	Maximum market share of renewables	15%	25%
		Learning rate for renewables investment costs	3%	7%
	Carbon capture and storage	CCS learning rate	7%	13%
		CCS start date	2015	2010
		CCS "bottleneck phase"	10 years	7 years
		CCS maximum market share at the end of the bottleneck phase	3.5%	5%
		CCS growth phase	8 years	8 years
		CCS maximum market share at the end of the growth phase	63%	90%
		CCS maturation phase	8 years	8 years
		CCS maximum market share at the end of the maturation phase	70%	100%
Low carbon end-use technologies	**Electric vehicles**	EV start	No significant market penetration	
		EV "bottleneck phase"		3 years
		EV maximum market share at the end of the phase		2.5%
		EV growth phase		15 years
		EV maximum market share at the end of the phase		45%
		EV maturation phase		16 years
		EV maximum market share		50%
	Industry	Capital lifetime in the industry	30 years	20 years
	Energy efficiency	Freight energy consumption	1	Trend extracted from POLES data: starts at 1 reaches 1.1 in 2030 and stays at 1.1 until 2100
		Freight fuel consumption elasticity to fuel prices	-0.35	-0.4
		Buildings energy consumption per m²[*]	Trend which starts at 1, reaches 1.2 in 2030 and stays at 1.2 until 2100	1

The parameters in bold are multiple parameters.

[*] different parameters according to the region.

[**] different parameters according to the region and horizontal slice in the annual monotonous load curve (between base load and peak load).

[***] different parameters according to the region and category of oil.

			Assumption 1	Assumption 2
Alternative liquid fuel supply	**Biofuels**	Time scale of reactive anticipation for biofuels production Biofuels supply: multiplier coefficient of the supply curves for the default value)	6 years Value from IEA curves	4 years 50% increase w.r.t Assumption 1 value
	Coal-to-liquids	Oil price threshold for CTL production start Time scale of reactive anticipation for CTL production Maximum production growth in 2030, 2035 and in 2050	200 $/bl 8 years 0.05 Mbd - 0.10 Mbd - 0.10 Mbd	120 $/bl 0 0.20 Mbd - 1.5 Mbd - 3 Mbd
Development patterns	**Transport**	**Motorization rate growth with GDP per capita***	50% increase w.r.t Assumption 2 value	Value from IEA data
	Buildings	Income elasticity of buildings stock growth Asymptote to surface per capita in China and India Start year and fuel price for a forced decline of oil consumption in this sector	1 60 2020 - 1300$/tep	0.7 40 2010 - 1000$/tep
	Industrial goods	**households industrial goods consumption saturation level [min-max]***(multiplier factor of the calibration year consumption volume)	[1.5-3]	[1-2]

The parameters in bold are multiple parameters.
* different parameters according to the region.

Chapter 9

Trade-Offs and Synergies in Urban Climate Policies: a quantitative analysis

This chapter is based on an article: *"Trade-Offs and Synergies in Urban Climate Policies"* (Viguié and Hallegatte, 2012).

   As explained in chapter 3, urban climate policies are not developed or implemented in a vacuum; they interact with other policy goals, such as economic competitiveness or social issues. These interactions can lead to trade-offs and implementation obstacles, or to synergies and win-win strategies. Despite a growing number of innovative urban climate strategies, little analysis investigating their effectiveness exists, in part because it requires a broad interdisciplinary approach that includes economics, urbanism, climate sciences, engineering and hydrology. Using NEDUM-2D-static (chapter 5), we provide here a first quantification of these trade-offs and synergies, to go beyond the qualitative statements that have been published so far. We undertake a multicriteria analysis of three urban policies: a greenbelt policy, a zoning policy to reduce the risk of flooding, and a transportation subsidy. We show that each of these policies appears to be undesirable because it has negative consequences with respect to at least one policy goal; however, in a policy mix, the consequences of each policy are not simply additive. This nonlinearity permits building policy combinations that are win-win strategies, contributes to mitigation and adaptation objectives that have co-benefits for other policy goals. In particular, we show that flood zoning and greenbelt policies are unlikely to be accepted if they are not combined with transportation policies. Our results also show that stand-alone adaptation and mitigation policies are unlikely to be politically acceptable and emphasize the need to mainstream climate policy within urban planning.

9.1   Introduction

Adaptation and emission reduction policies rely on the same tools, giving rise to both synergies and conflicts (McEvoy et al., 2006; Hamin and Gurran, 2009). Synergies and conflicts with other policy goals also exist, and environmental policies can result in positive feedback with respect to economic and social issues. For instance, a decrease

in car congestion increases residents' quality of life, enhances economic competitiveness, reduces accessibility inequalities among neighborhoods, and decreases air pollution and GHG emissions. Conversely, while enlarging parks and introducing more vegetation in cities can be a useful way to adapt cities to higher temperatures and can improve the quality of life, such actions may also reduce population density and lead to increased GHG emissions from transportation. Similarly, protecting urban coastlines with dikes and seawalls decreases cities' vulnerability to floods, but can reduce recreational amenities and a city's attractiveness to tourists, thereby reducing inhabitants' incomes and slowing down development. All policies have consequences for property values, which in turn influence the attractiveness of an urban area for potential residents, professionals, and businesses. These effects can vary by community or location, for example, impact in the suburbs versus that in the city center, leading to unintended redistributions of wealth or amenities that may or may not be consistent with policy goals.

Such conflicts among different policy goals create implementation problems, while synergies offer opportunities for win-win solutions, suggesting the utility of assessing all urban policies within a unified framework (Munasinghe, 2011). Building such a framework requires aggregating results from different research fields in an interdisciplinary analysis. Moreover, because urban management implies political choices and value judgments, urban climate policies have to be judged using multiple criteria (Hallegatte et al., 2010).

In this context, a pertinent tool is integrated city models (ICMs) (for an example see Solecki and Oliveri, 2004). ICMs are highly simplified representations of reality that describe the most important drivers of city change over time and can assess the consequences of various policy choices. ICMs can provide decision makers and stakeholders with useful information and can help them understand the main mechanisms and linkages at work.

We propose a multicriteria analysis of synergies and trade-offs with respect to urban climate policies aimed at mitigation and adaptation using a simple ICM, NEDUM-2D, which is described in the supplementary online material. Our analysis focuses on Paris, but its results are generic and most of its conclusions are valid for many cities. Using this model, we show that urban policies are best assessed by means of an integrated framework using multiple criteria that correspond to numerous policy objectives. We find that building a policy mix that has positive effects for all objectives is possible. In other words, cities' mitigation, adaptation, economic, and social policies can be made synergetic if they are designed in such a way that each policy takes other policies into account.

9.2 Policy goals and indicators

In this analysis, we assess urban policies with respect to five policy goals: climate change mitigation, climate change adaptation and disaster risk reduction, natural area and biodiversity protection, housing affordability, and ease of implementation (including affordability). These goals can be translated into quantitative indicators in many ways. As an illustration, we suggest five possible and relevant ones that our ICM can measure and model (Tab. 9.1). Indicator choice is a crucial issue that depends on the objectives for a given policy and on decision makers' priorities. Moreover, for all practical purposes, indicators should be chosen in collaboration with stakeholders and policy makers (Corfee-Morlot et al., 2009).

Policy goals	Indicators
Climate change mitigation	Average distance traveled by car for commuting
Adaptation and natural risk reduction	Population living in flood-prone areas
Natural area and biodiversity protection	Total urbanized area
Housing affordability	Average dwelling size in the center of the urban area
Implementation easiness	Gini index of real estate investments profitabilities

Table 9.1: List of policy goals and proposed indicators.

The indicators we utilize do not encompass all possible policy impacts on the five policy goals, but are informative for the policies we will be considering as follows (See Section 1 of Supplementary Information for a full description of the indicators), and each can be directly measured:

- Climate change mitigation: Urban policies can influence GHG emissions resulting from transport, heating, and air conditioning. Here we focus on transportation emissions. Our proposed indicator, the average distance traveled by car for commuting, is a simple proxy for GHG emissions in the absence of comprehensive modeling of urban GHG emissions.

    – *In the model, we only consider commuting trips assimilated to trips towards the center of Paris. These trips can be made either using public transport or using private vehicles : transport mode choice is computed through an optimization of generalized transport cost, comparing trip duration and trip price for public and private transport. The indicator is the average distance traveled by car by households in the city.*

- Climate change adaptation and disaster risk reduction: In Paris, one of the main disaster risks is flooding, and climate change may increase this risk, even though models still disagree. We therefore use the population living in flood-prone areas as an indicator. Heat wave vulnerability is another important topic, but it can only be investigated by coupling the urban model with a urban microclimate model (Masson, 2000b).

    – *Flood-prone areas are defined by the extent of extreme historical floods. In model simulations, the total population living in these areas is in good agreement with empirical measurements : in 2010, approximately 490 000 households live in such areas in Ile de France (Paris administrative region) (Laporte, 2009), whereas in model simulations this figure is 520 000. The indicator is the number of households living in flood-prone areas.*

- Natural area and biodiversity protection: The transformation of natural areas into urbanized area has many environmental impacts, for example, on biodiversity and water and flood management. For this policy goal we use the total urbanized area as an indicator. We measure the total area where more than half of the ground surface has been artificialized.

- Housing affordability: Access to housing plays an important role in the quality of life and the competitiveness of a city. Improving housing affordability can therefore be both a social and an economic objective. This is particularly crucial in most major cities and can be measured using either rents or average dwelling size. Either of these two indicators can be used, because they are correlated: everything else being equal, households live in larger dwellings when rents are lower. Here we use average dwelling size in the center of the urban area as an indicator.

- Ease of implementation (including affordability): Policy benefits need to be compared with policy costs, especially for public finances, but even when the cost-benefit analysis is positive, a policy can encounter other political or institutional implementation obstacles. In particular, even if a policy has a positive impact as measured using aggregated indicators, it may have large unintended redistributive effects or particularly large negative effects on one category of residents or on one area of the city. Such redistributive effects often make implementation difficult or require corrective measures. To build a quantitative indicator of these effects, we start with the spatial distribution of returns on real estate investments in the city and calculate the spatial Gini index of the profitability of real estate investments. A high value of this indicator means that the evolution of a city leads to large changes in relative land prices, causing unintended wealth redistribution. A policy that increases this indicator is amplifying this redistribution impact and is supposedly politically more difficult to implement.

  - *We measure real estate investments profitabilities as the relative increase in land prices between 2010 and 2030. The indicator we measure is the Gini index of all relative land price increase in the urban area, weighted by available ground surface. If the Gini index is high, it means that land prices follow different trajectories in different locations, creating wealth redistribution. Without any urban policy, the natural evolution of the city leads to such a redistribution because of population and technology changes. We consider as positive a policy that compensates these unintended transfers, and as negative a policy that enhances them.*

9.3 Modelling assumptions

The NEDUM-2D-static model is used to simulate the evolution of the Paris urban area between 2010 and 2030. This model is described in chapter 5. The future of Paris urban area depends on several external factors, including demographic, socio-economic, cultural and political changes. Future public transport and private vehicle travel costs (which take into account variation in technologies, oil prices, taxes, etc.) and future households income are extrapolated over the 2010–2030 period, from observed average growth rate in Paris urban area between 1988 and 2008. Future population and households size are taken from the central demographic scenario for Paris urban area developed by INSEE, the French statistical organization, and IAU, the Ile-de-France urbanism agency. Our conclusions are robust to changes in these values, as shown by a sensitivity analysis (see Supplementary Online Material).

Many different assumptions about the future development of transport infrastructure can be made and tested with the model. For simplicity, we suppose here that it remains unchanged between 2010 and 2030, and that congestion on roads and public transport remains constant, i.e. future investments in the transportation network
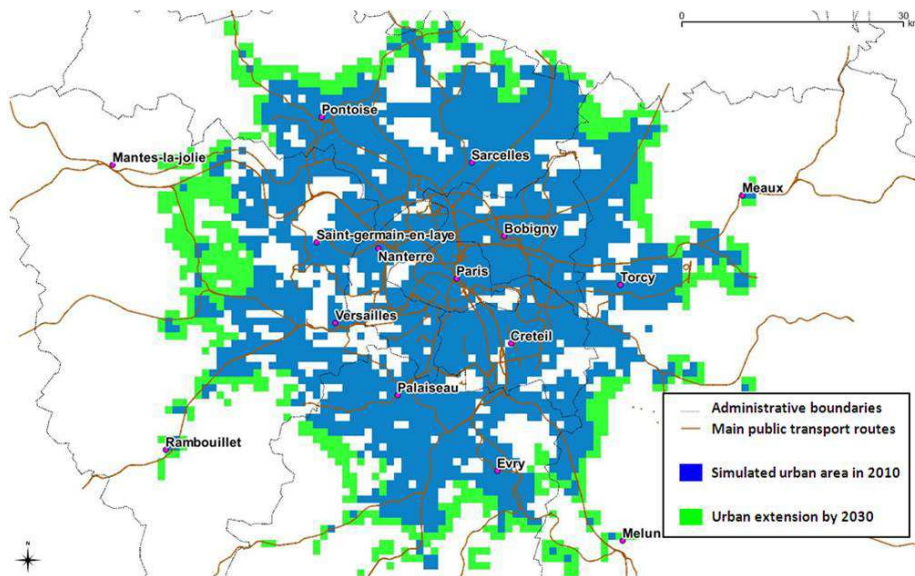
Figure 9.1: Map of total urbanized area in 2010, and in 2030 in the do-nothing scenario.

are assumed to maintain the same service level in spite of population growth, without developing new lines.

9.4 Urban Policies

We consider three policies that aim at different targets, but have consequences on the aforementioned five goals: a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding. We compare theres policies to a do-nothing scenario, whereby urbanization is driven only by market forces and the external drivers (transport costs, population, etc.). These boundary conditions are described in Appendix 9.A.

Figure 9.1 illustrates the do-nothing scenario. The model projects a significant extension of the urbanized area between 2010 and 2030 as a result of increased population and decreasing transportation costs relative to income.

The first policy is a greenbelt policy whereby land use regulations prohibit building in areas that are not already densely inhabited.[1] This policy aims at limiting urban sprawl and at protecting natural areas. With this policy, the urbanized area in 2030 is the same as in 2010, even though building and population densities are different. As table 1 shows, this policy also limits the increase in private vehicle usage, increases real estate prices, and reduces dwelling sizes by making land more scarce. This increased land scarcity leads more people to live in flood-prone areas, which has been empirically observed (Burby et al., 2001; Lall and Deichmann, 2010).

The second policy is a public transport subsidy financed by a lump sum tax.[2] We

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[1] We supposed in this policy that building is possible only in locations where more than half of ground surface is already built-up in 2010. In other locations, new buildings are forbidden and existing buildings cannot be enlarged.

[2] Differentiated public transport tariff, increasing with the distance from city center, is replaced by a

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Indicators	Greenbelt	Public transport subsidy	Flood risk zoning	Policy mix	Do-nothing scenario
Variation in average daily distance driven in car (m)	+ 1570	-440	+ 2550	-880	+ 2560
Variation in population in flood-prone areas (thousands of households)	+ 39	-4	-6	-8	+ 6
Variation in total urbanized area (km^2)	0	+ 690	+ 470	0	+ 480
Redistributive impacts (Gini index)	+ 0.093	+ 0.271	+ 0.201	+ 0.146	+ 0.203
Variation in dwelling size in the center of Paris (m^2)	+ 0.17	+ 1.73	+ 0.79	+ 0.95	+ 0.82

Table 9.2: Multicriteria analysis of urban policies on Paris in 2030 with respect to the five policy goals.
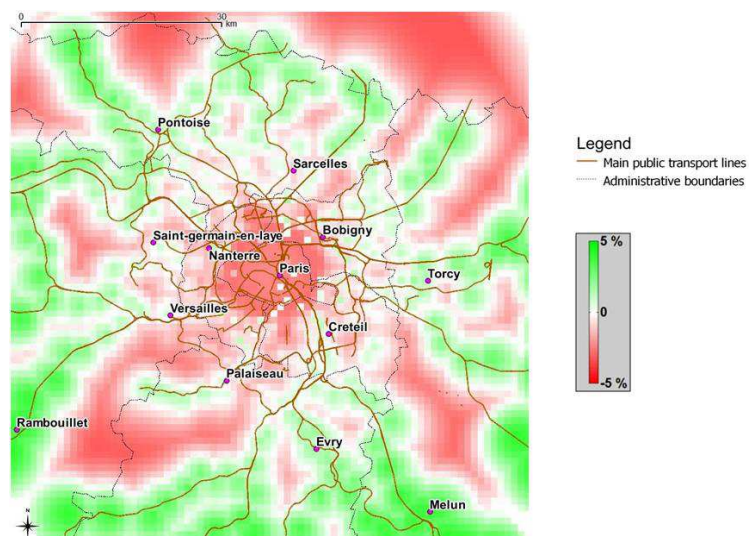

Figure 9.2: Rents in the public transport subsidy scenario compared to rents in the "do-nothing" scenario.
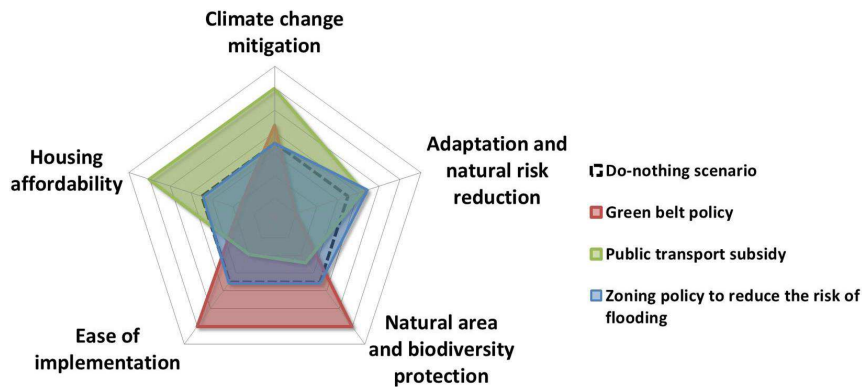
Figure 9.3: Consequences of a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding compared with the do-nothing scenario.

take the example of the recently proposed replacement of the differentiated public transport tariff—which increases with distance from the city center—by a single tariff for all destinations in the Paris urban area. Such a policy aims at promoting public transport, as well as decreasing the burden of transport costs on suburban households, which in Paris are, on average, poorer than those living in central Paris. The side effects of such a policy are to increase the incentive to live farther out in the suburbs, leading to an increase in the total urbanized area and to a decrease in real estate pressures in the city center (cf. Fig. 9.2).

The third policy is a zoning policy to reduce the risk of flooding.[3] This policy prohibits new buildings in flood-prone areas. Such a policy reduces the available urban ground surface, thereby increasing land scarcity, and causes a slight general increase in housing prices, leading to smaller dwelling sizes in the city center.

Figure 2 presents the results graphically for the three policies. The impact of each policy on each indicator has been assigned a score and is located along one of the five axes of the figure. The -100 percent score is in the middle of the figure; the +100 percent score is at the extremity of each axis. All scores are measured relative to the do-nothing scenario, which is assigned a 0 percent score. The +100 percent score goes to the preferred outcome among all considered policies. Each policy is thus ranked best when the corresponding colored area is biggest. For instance, Fig. 2 shows that a public transport subsidy improves the situation compared with the do-nothing scenario for three policy goals (climate change mitigation, housing affordability, and adaptation and disaster risk reduction), and makes it worse with respect to two policy goals (natural area and biodiversity protection and ease of implementation).

single tariff for all destinations in Paris urban area. This new tariff is equal to 20% of the lowest tarif for all destinations in do-nothing scenario. The money needed to finance this policy is obtained through a flat income tax.

[3]This policy prohibits new buildings and enlargement of existing ones in flood-prone areas, after 2010. As in the measurement of population living in flood-prone areas, these areas are defined by the extent of extreme historical floods.
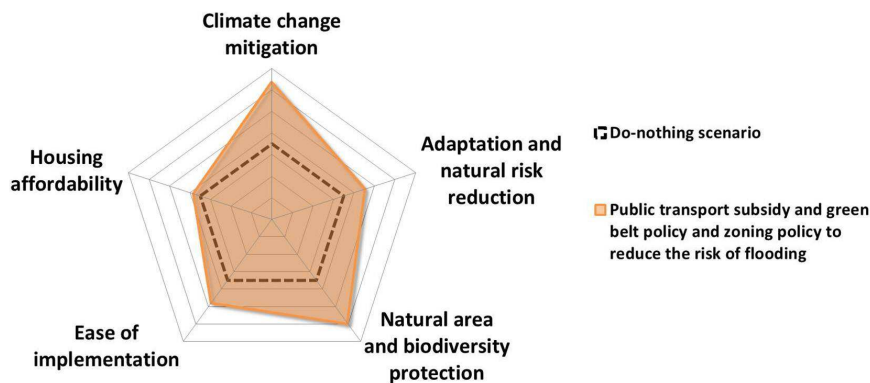
Figure 9.4: Consequences of a policy mix including all three policies.

9.5 Policy Mix

As Fig. 2 shows, each policy causes both positive and negative outcomes with respect to different policy goals when compared with the do-nothing scenario. However, as Fig. 3 shows, a policy mix that includes these three policies can mitigate the adverse consequences of each individual policy. For instance, public transport subsidies decrease the real estate pressures caused by a greenbelt policy, and banning building in flood-prone areas limits the resulting increase in population in these areas. When all three policies are applied together, the situation is improved as measured along all policy goals compared with the do nothing scenario.

Note that in a policy mix, the consequences of each policy are not simply additive. For instance, when all three policies are implemented, the decrease in population in flood-prone areas is smaller than the sum of the variation caused by each policy taken separately. This nonlinearity and the complexity of policy interactions explain why analyzing various urban policies together, in a consistent framework and with an integrated modeling tool like NEDUM-2D, is useful.

Of course the preferred policy mix depends on the weight attributed to each criterion, and a negative outcome for one policy goal can be more than compensated for by an improvement for another. Also, other criteria may be necessary for a complete analysis, for example, introducing differentiated criteria for the short term and the long term. Regardless of these limitations, our analysis shows that building win-win solutions by combining policies with different consequences is possible. Even though the institutional fragmentation of urban policies does not always allow for such an integrated decision-making process (OECD, 2006), this type of analysis may help identify policies that are more efficient and have higher political acceptability.

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Appendix 9.A Scenario and boundary conditions

The scenario we simulate is not in any way a forecast of future evolution of the Paris urban area. Instead, it represents a consistent and possible scenario, which can help understand main drivers of urban evolution and the impact of various policies.

The model can be used to test many different assumptions about the future development of transport infrastructure. For simplicity, we assume that it remains unchanged between 2010 and 2030 and that congestion on the roads and public transport remains constant, that is, we assume that future investments in the transportation network maintain the same level of service despite population growth.

	Value in 2010	Low hypothesis for 2030	Central hypothesis for 2030	High hypothesis for 2030
Private vehicle usage cost (€/km)	7.1	5.8	7.6	9.8
Minimum monthly public transport pass price (€)	47.4	61.7	71.5	93.0
Households income (€/year)	51 000	78 000	89 000	91 000
Urban area population (number of households)	5 255 000	5 566 000	5 859 500	6 163 000

Table 9.3: Techno-economic and demographic scenarios data

The evolution of the Paris urban area depends on several external factors, including demographic, socioeconomic, cultural, and political changes. The model thus requires input assumptions on these factors. To provide these inputs, we extrapolate the future costs of public transport and private vehicles (taking into account changes in technologies, oil prices, taxes, and so on) and of household incomes over the 2010-30 period based on the average growth rate in the Paris urban area between 1988 and 2008. We took future population and household sizes from the central demographic scenario for the Paris urban area developed by the Institut national de la statistique et des études économiques, the French statistical organization, and from the Institut d'aménagement et d'urbanisme, the urbanism agency for the Ile-de-France area. The data we used are listed in the "Central hypothesis for 2030" column of Tab.9.3.

Appendix 9.B Results and sensitivity analysis

Table 9.4 reproduces quantified results from the model, in the five scenarios (greenbelt policy, public transport policy, flood risk zoning, policy mix, and do-nothing scenario), for the five indicators. Of course, the model provides more detailed information, and especially geographic information on the spatial impact of a given policy. For instance, the impact of the public transport subsidy on rents and real estate prices is shown in Fig. 9.2.

To test the sensitivity of our conclusions to scenario choice, we computed 81 scenarios by letting our scenario parameters vary. Alternatives for public transport prices, private vehicle travel prices, and households income growth rate correspond to maximum and minimum observed growth rates (averaged over 5 years) in Paris urban area

Indicators	Greenbelt	Public transport subsidy	Flood risk zoning	Policy mix	Do-nothing scenario
Variation in average daily distance driven in car (m)	+ 1570 *(90/ 3070)*	-440 *(-2140/ 900)*	+ 2550 *(290/ 4860)*	-880 *(-2180/ - 70)*	+ 2560 *(290/ 4870)*
Variation in population in flood-prone areas (thousands of households)	+ 39 *(4/ 84)*	-4 *(-36/ 29)*	-6 *(-44/ 18)*	-8 *(-25/ 8)*	+ 6 *(-37/ 65)*
Variation in total urbanized area (km^2)	0 *(-30/ 0)*	+ 690 *(510/ 880)*	+ 470 *(90/ 750)*	0 *(-20/ 0)*	+ 480 *(80/ 760)*
Redistributive impacts (Gini index)	+ 0.093 *(0.043/ 0.131)*	+ 0.271 *(0.237/ 0.326)*	+ 0.201 *(0.049/ 0.273)*	+ 0.146 *(0.136/ 0.174)*	+ 0.203 *(0.042/ 0.275)*
Variation in dwelling size in the center of Paris (m^2)	+ 0.17 *(-1.47/ 1.17)*	+ 1.73 *(0.6/ 2.55)*	+ 0.79 *(-1.21/ 1.94)*	+ 0.95 *(-0.15/ 1.73)*	+ 0.82 *(-1.1/ 1.96)*

Table 9.4: Multicriteria analysis of urban policies on Paris in 2030 with respect to the five policy goals. The numbers are the median value over all exogenous socio-economic scenarios (income, transport prices and technologies). The number in parenthesis are the extreme values when changing scenarios.

between 1988 and 2008. Alternatives for population and household size growth are based on high and low demographic scenarios for Paris urban area developed by IN-SEE, the French statistical organization and IAU, Ile-de-France urbanism agency. Alternative scenario parameters are summarized in Tab.9.3.

As can be seen on Tab. 9.4 and Fig. 9.5(a), 9.5(b) and 9.5(c), policies outcomes depend strongly on the selected world scenario. However, the relative impact of each policy for the different policy goals is not sensitive to this scenario choice, making the decision-making almost independent of this choice. The policy-mix improves the situation for all policy goals compared to the do-nothing policy in 65% of all scenarios. A policy-mix with a stronger transport subsidy or a private vehicle tax enables to increase this percentage.
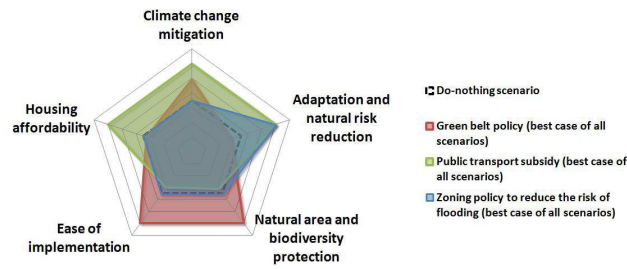
(a) Best cases of all scenarios.
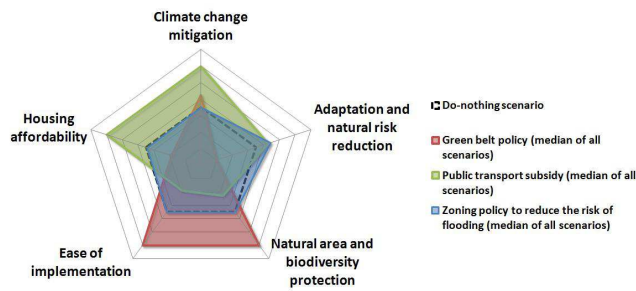
(b) Median of all scenario
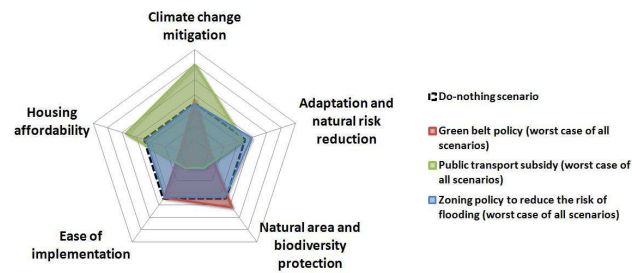
(c) Worst cases of all scenarios

Figure 9.5: Consequences of a greenbelt policy, a public transport subsidy, and a zoning policy to reduce the risk of flooding compared with the do-nothing scenario.

Conclusion and perspectives

Cities play a key role climate change policies : firstly, land use planning and urban transport and housing policies are major tools of climate change mitigation, and secondly, a high concentration of population and economic activity makes cities particularly vulnerable to climate change impacts and requires specific adaptation measures. Because of the long lifetimes of buildings and the high inertia of city structures, immediate action is required if cities are to be adapted to a different climate or to help reduce GHG emissions within a few decades.

Integrated city modeling can help address urban climate issues : it captures the complex impact of global variables, such as oil prices and transport prices, on local evolutions of a city. It enables also to capture the interactions between different city parameters, and analyze the interdependency of various urban policy objectives.

The model NEDUM-2D, captures main long-term determinants of city evolution: it reproduces the main tendencies of past Paris urban area evolution. It is simple enough to enable testing deep changes in a city structure, takes into account the uncertainty on a city future and keeps its processes and conclusions clear, avoiding a "black box" effect.

In this work, we have analyzed three issues with which climate policies have to deal. First, in line with the works of Gusdorf (2008), inertia is a key factor when designing optimal climate policies. Indeed, various variables of a city evolution are characterized by different evolution timescales. The long and short term impacts of urban policies can therefore be very different. Our analysis, in Chapter 7, of the impact of 100€ /tCO$_2$ a carbon tax on Paris urban over the short, medium, and long term illustrates this phenomenon : whereas redistributive effects of this measure can happen very quickly, effects on households location happens only over the long-term.

Second, uncertainty plays a key role in urban climate policies assessment. Urban decision-makers generally do not have total control on household's behaviour and on the evolution of their city. They can only try to redesign their city through some constraints imposed on spontaneous urban development. This spontaneous development is influenced by many external factors (lifestyles evolution, transport technologies etc.) which future evolution is unknown. Robustness against this uncertainty should therefore be a key element in urban climate policies appraisal and prospective studies are essential. In Chapter 8, we have shown how it is possible to downscale global world evolution scenarios until 2100 (such as SRES scenarios, cf. Nakicenovic et al., 2000) at city scale, and design possible and coherent scenarios, which represent conceivable futures.

This enables to show, that, in Paris urban area, main drivers of urban sprawl and climate and flood vulnerability appear to be local demographic growth and local policies. Global factors, such as energy and transport prices, even including possible peak-oil

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and carbon taxes, have only a limited influence on them. Conversely, transport-related greenhouse gases emissions are mainly driven by global factors, namely vehicle efficiency changes, not by land use. As a consequence, very strict urban policies — including reconstruction — would become necessary to control emissions from urban transportation if technologies reveal unable to do so.

Finally, urban adaptation and mitigation policies interact with each others, and with other policy goals, leading to synergies and conflicts. So far, only qualitative analysis of these interactions have been developed, and knowledge is lacking on the relative importance of these interactions, and on the effectiveness of policies aiming at counterbalancing side-effects. In Chapter 9, we have done a first quantification of these interactions. We have shown that urban policies are best assessed by means of an integrated framework using multiple criteria that correspond to numerous policy objectives. We find that building a policy mix that has positive effects for all objectives is possible. In other words, cities' mitigation, adaptation, economic, and social policies can be made synergetic if they are designed in such a way that each policy takes other policies into account.

If some first results were obtained through this work, many developments can be done do deepen the analysis of the three issues we have presented. First, calibrating the model on other cities, with characteristics as different as possible from French cities (a rapidly-growing developing country city and an Eastern Europe shrinking city, for instance), would also enable to better understand the validity of our model. For instance, it would be especially interesting to calibrate the model on a fast growing developing world city, and on a East European shrinking city.

Our analysis of inertia and of the consequences of climate policies over time could be refined by making the model slightly more complex: For instance, as our modeling is monocentric, it was not possible to simulate the effect of an increased development of other subcenters in the urban area. Such a development would greatly change travel patterns and the urban form, resulting in alternative scenarios. A more complex, polycentric model would be useful to test the influence of other new variables, and especially investment in services supply (schools, health, leisure...) across the urban area. This is the subject of our present research. Jobs and activities localization dynamics would also be of great interest and would enable to study the influence of urban climate policies on the job market.

A better depiction of transport systems would also enable to refine our conclusions. A better modelling of modal choices and of congestion would be especially useful to be able to describe more accurately transport policies. Coupling the model with urban transport models could be profitable.

Our analysis of uncertainty could also be improved. We have only considered here a small number of scenarios; to assess the robustness of our results, other scenarios could be downscaled. Our analysis might also gain from deeper analysis following robust decision-making literature concepts and approaches.

The study of side-effects and tradeoffs, could benefit from a better integration with risk models. To investigate this topic, three on-going research projects[4] are coupling this urban model with the urban microclimate model TEB. This model could be also coupled with other models, for instance, with an hydrological model, to assess flood-risk evolution because of climate change and of urban sprawl. Another possibility

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[4]VURCA, MUSCADE and ACCLIMAT projects (http://www.cnrm.meteo.fr/ville.climat/?lang=en).

would be to couple it with an urban air circulation model, to study urban shape evolution on urban pollution.

Another development direction is to take into account diversity in households types, for instance by dividing households in several income classes. This would for instance enable to study urban policies differentiated impacts on poor or rich households.

Finally, it would also be interesting to apply in our analysis more complex multi-criteria decion-making techniques, which might enable to highlight more complex tradeoffs or more efficient strategies.

As a conclusion, these results represent a first step in a long-term research program on urban dynamics and environmental policies.

List of abbreviations

GHG Greenhouse Gases

ICM Integrated City Model

IEA International Energy Agency

LUTI model Land-Use Transport Interaction model

Mtoe Million Tonnes of Oil Equivalent

SLR Sea Level Rise

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Abstract

Because they are home to more than half of the world population, and because most of the world economic activity takes place within them, cities are at the forefront of global environmental issues. Land use planning, urban transport and housing policies are now recognized as major tools for the reduction of both greenhouse gases emissions and vulnerability to climate change impacts. So far, however, how to use these tools efficiently remains unclear. At least three main difficulties explain this, and play a key role in urban climate policies analysis. First, urban climate policies are also not developed or implemented in a vacuum; they interact with other policy goals, such as economic competitiveness or social issues, giving rise to both synergies and conflicts. Second, inertia is a key factor when designing optimal climate policies: structural modifications in cities occur slowly over a long time horizon. Some immediate actions are required if cities are to be adapted to a different climate or to help reduce greenhouse gases emissions within a few decades. Third, the evolution of a city depends on several external factors, on which local policy-makers do not generally have much influence: demographic, socio-economic, cultural, political and technological changes will play a major role. This uncertainty has to be taken into account, and climate policies have to be robust against future possible global evolutions is important. These three difficulties are not, however, impossible to overcome, and we will illustrate how integrated city modelling can help address these issues.

Résumé

Parce qu'elles concentrent plus de la moitié de la population et l'essentiel de l'activité économique mondiales, les villes sont des acteurs majeurs des problématiques environnementales globales. Les politiques de transport, d'urbanisme et de logement sont ainsi reconnus comme des moyens nécessaires et efficaces d'action pour réduire les émissions ainsi que pour réduire la vulnérabilité aux impacts du changement climatique. Jusqu'à présent, malheureusement, il n'y a pas de consensus sur ce qui doit être fait, et encore moins sur comment le faire. Trois difficultés, au moins, expliquent cela. Tout d'abord, les politiques climatiques interagissent avec les autres objectifs des politiques urbaines, comme la compétitivité économique ou les problèmes sociaux, entrainant des synergies et des conflits. Ensuite, les inerties sont un facteur-clef à prendre en compte : les modifications structurelles des villes s'opèrent très lentement. Si l'on veut que les villes soient adaptées au climat de la fin du XXIème siècle, il est indispensable de commencer à agir dès maintenant. Enfin, les effets des politiques urbaines dépendent de nombreux facteurs exogènes, et inconnus au moment où la décision doit être prise : les changements démographiques, socio-économiques culturels politiques et technologiques vont jouer un rôle majeur. Ces trois difficultés ne sont cependant pas insurmontables, et nous illustrerons comment une modélisation intégrée peut permettre de répondre à une partie de ces problèmes.