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# THE ECONOMICS OF CLIMATE CHANGE IMPACTS AND POLICY BENEFITS AT CITY SCALE: A CONCEPTUAL FRAMEWORK

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*Keywords : Climate; Natural Disasters; Global Warming; Sustainable Development; Government Policy; General Macroeconomics; Regional, Urban and Rural Analyses; Regional Economics*

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# ABSTRACT

Cities are particularly vulnerable to climate change and climate extremes because they concentrate many activities, people and wealth in limited areas. As a result they represent an interesting scale for assessment and understanding of climate change impacts as well as for policy assessment.

This paper provides a conceptual backdrop for urban economic impact assessment of climate change and its specific aim is to provide both a conceptual and a methodological framework for OECD work in this area. The scope includes the assessment of the potential incidence and economic cost associated with changes in extreme events in cities. Given the broad uncertainties about how climate policies play out, this paper proposes to address these through a comparison of impacts under different mitigation strategies and different adaptation scenarios. Such an approach provides a means to bracket uncertainty about both mitigation and adaptation responses. The focus here is on model-based analysis of future scenarios, including a framing of uncertainty for these projections, as one valuable input into the decision-making process. It is of course imperative that cities not wait for perfect information, that they take action now to incorporate up to date knowledge about climate change into near-term decisions and long-term planning.

Assessing local economic impacts of climate change enhances understanding about how urban development interacts with climate change over time and highlights public policy or private choices to address and limit such impacts. The paper highlights the main assessment difficulties, methods and tools, and selected examples across these areas. A number of challenges are unique to climate change impact assessment and others are unique to the problem of working at local scales. The paper also identifies the need for additional research, including on the need for more integrated approaches to address climate change as a part of the urban development challenge and on approaches to assess the economic impacts of climate change at local scale.

There is a back and forth relationship between development and climate change. That is, development, greenhouse gas mitigation and adaptation choices are intertwined and proceed in parallel with each other. Nevertheless the assessment of the economic impacts of climate change requires a step-wise analysis and starts from assumptions or scenarios about the future of development. The paper is therefore organised along a simple causal chain that begins with socio-economic development to global climate change to economic damages at the city level. It does not attempt to address the important question of how to use such information to support adaptation decision making. The focus remains more narrowly on the dimension of impacts assessments at local scale.

As a first step, the paper identifies the need for a global socioeconomic and emission scenario to derive information needed to carry out an impact assessment. It is then necessary to downscale the socio-economic scenario using assumptions about key issues such as future rates of urbanization and the pace and shape of urban economic development. A second step is to develop regional climate predictions from global emission scenario and climate predictions, using downscaling methodologies. The third step draws upon this information to estimate the physical and economic impacts of climate change at local scale, taking into account that all economic agents will respond to climate impacts by implementing adaptation strategies.

Cities function as integrated systems, consisting of many closely interlinked sectors of economic activity and types of infrastructure. The evaluation of economic impacts begins by identifying and estimating direct economic losses at the sector level. But these direct losses can be amplified by spatial or sectoral diffusion into the wider economic system, causing significant systemic losses that depend on complex interactions across a range of different economic factors. As a result, direct losses are only a fraction of total economic losses; indirect losses also need to be estimated. To carry out a complete assessment, local co-benefits (and co-costs) of adaptation and mitigation should also be taken into account.

Despite the uncertainties surrounding the analysis, economic impact estimates allow for a better understanding of the human activities affected by climate. City-scale assessments of the impacts of climate change can provide local decision-makers with a better understanding of the benefits of aggressive mitigation strategies, by “localising” that understanding, and have immediate value to bring attention to climate change amongst local decision-makers and to inform debate about the range of possible response options. Ideally such assessments are developed in consultation with stakeholders who bring essential insights and local knowledge about long term development preferences that should be incorporated into socio-economic scenarios. By providing up to date information about climate change risks, such assessments also provide one important input to adaptation decision making.

**JEL classification**: Q01, Q51, Q54, Q56, Q58, R00.

**Keywords** : Climate; Natural Disasters; Global Warming; Sustainable Development; Government Policy; General Macroeconomics; Regional, Urban and rural Analyses; Regional Economics

# FOREWORD

Climate change has become a priority issue in global environmental governance and cities are important players. For over three decades, the OECD has been actively supporting member and non-member countries to design environmental policies that are both economically efficient and effective at achieving their environmental objectives.[1] Through peer reviews of policy implementation, the OECD helps governments to improve their collective and individual environmental performance, through sound economic and policy analysis and dialogue on how to establish and to achieve climate change goals. Climate change has been on the agenda since the late 1980s at the OECD, where we provide a forum for countries to, discuss and develop a shared understanding of the key policy challenges as well as to assess performance and identify good practice in the design and implementation of climate policies.

Today the OECD is actively working with governments to highlight the role of cities to deliver cost-effective policy responses to climate change. A number of projects at the OECD are advancing the understanding of the roles that cities can play to respond to efficiently and effectively to climate change.

This report is one in a series under the OECD Environment Directorate's project on Cities and Climate Change. The project aims to explore the city-scale risks of climate change and the local benefits of both adaptation policies and (global) mitigation strategies.

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There is also a website dedicated to this work with links to related work on cities across the OECD. Please see:

- www.oecd.org/env/cc/cities

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[1] The OECD is an intergovernmental organisation, representing 30 member countries, all of whom are committed to common principles to support economic development including social and environmental protection. More information is available on our home website: www.oecd.org

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## 1. Introduction

Cities are increasingly active in the implementation of climate change solutions. A key challenge for local actors is to understand the nature of future climate change risks in their region and to identify the main drivers of urban vulnerability. Better understanding climate change impacts will assist local authorities to communicate with local, other sub-national and national decision makers, to mobilise political will, to assess options and to design cost-effective and timely responses. The need for a foundation of knowledge about local impacts and vulnerability represents an opportunity for a fruitful two-way exchange between climate change scientists and impact experts on the one hand, and local and national decision-makers on the other. Ultimately it is a means to advance understanding about the risks of climate change in local contexts and to motivate and empower action across scales to address climate change.

The topic of cities and climate change has recently become an active area of research. Relevant activities include the Tyndall Centre in the UK[2] with their project "*Engineering Cities: how can cities grow while reducing vulnerability and emissions?*" and the German Potsdam Institute for Climate (PIK) led European-wide project "*Urban lifestyles, sustainability and integrated environmental assessment.*"[3] In France, the "Sustainable City" program of the National Research Agency also aims at improving knowledge on urban vulnerability to climate change[4]. In a few large US cities, a number of scholarly studies exist to assess impacts and vulnerability, sometimes with a focus in key areas, notably in New York City, for example the "*New-York Climate and Health Project.*"[5] These works tend to tackle different aspects of environmental risk in cities, taking climate change into account as one among many drivers of environmental change risks, such as flood risks (De Roo, *et al.,* 2007; Hallegatte *et al.*, 2008c) and water system management (Rozensweig *et al.,* 2007), epidemiologic impact of ozone and fine particles pollution (Bell *et al.,* 2007), and heat-related mortality (Dessai 2003; Knowlton *et al.*, 2007). More generally a few cities appear to be at the forefront of adaptation[6] (*e.g.*, Chicago, London, Miami, Paris, Toronto) and a number of umbrella groups have grown up to assist cities to learn from each other as they develop capacity and experience in this area.[7]

Despite the proliferation of city-scale research, the assessment of the economic impacts of climate change at this scale has received little attention. To date most of the literature on economic impacts of climate change (often referred to as damage costs) has been focused on global scale impacts (*e.g.* IPCC 2007b & c; OECD 2008; Stern 2006; Tol 2002a&b). There is also a relatively large literature critiquing available damage cost estimates for global or world regions as being at best partial when used in formal economic analysis of policies (see OECD 2004 for a review; Fisher & Nakicenovic *et al.,* 2007; Schneider *et al.,* 2000). In recent years, some local economic impacts analysis has emerged to demonstrate the value of city-scale work (*e.g.* in Alexandria, Boston, Chicago, Copenhagen, London, Mumbai, New York, see a review in Hunt and Watkiss, 2007). However given the paucity of work in this area, more generally, the

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[2] See: http://www.tyndall.uea.ac.uk/research/programme6/scopingstudy.html

[3] See: FP4 ULYSSES http://www.pik-potsdam.de/research/past/1994-2000/europa/euro9.html

[4] Agence Nationale de Recherche http://www.agence-nationale-recherche.fr/appel-a-projet/21?lngAAPId=196

[5] See: http://directory.ei.columbia.edu/displayproject.php?projectid=150

[6] See Chicago Climate Action Plan (2008) and Parzen (2008); Greater London Authority (2008); Miami-Dade County Climate Change Advisory Task Force (2008); Mairie de Paris (2007) ; Toronto Environment Office (2008).

[7] See: Urban Leaders Adaptation Initiative [http://www.ccap.org/index.php?component=programs&id=6] ; Alliance for Resilient Cities (ARC) [http://www.cleanairpartnership.org/arc.php]; and ICLEI's Climate Resilient Communities in the US and adaptation work in Europe: [http://www.iclei.org/].

OECD designed this project to focus on the need for bottom-up, local and regional scale assessments to inform cross-scale decision-making and to provide important empirical evidence to improve global assessments of impacts and vulnerability.

This paper is part of a larger body of OECD work focused on cities and climate change. It aims to explore local benefits of climate change policies and the linkages between national and local climate policy response. Climate change is likely to increase the risk of certain extreme events but the potential damages from increased severity of extreme climate events are often not included in economic analysis (IPCC, 2007b, ch19). One of the aims of the OECD project is thus to include in these local assessments the potential incidence and economic cost associated with changes in extreme events in cities. Cities concentrate many activities, people and wealth in limited areas and as a result they are particularly vulnerable to climate change and climate extremes. The underlying assumption of the work is that understanding and estimating local vulnerability will assist decision-makers to manage vulnerability to climate change.

This paper provides a conceptual backdrop for the assessment of local, economic impacts of climate change. The focus is on urban contexts, however many of the issues and suggestions are also relevant to rural or broader sub-national regional impact analysis. The specific aim of the paper is to provide a methodological framework for OECD work in this area.

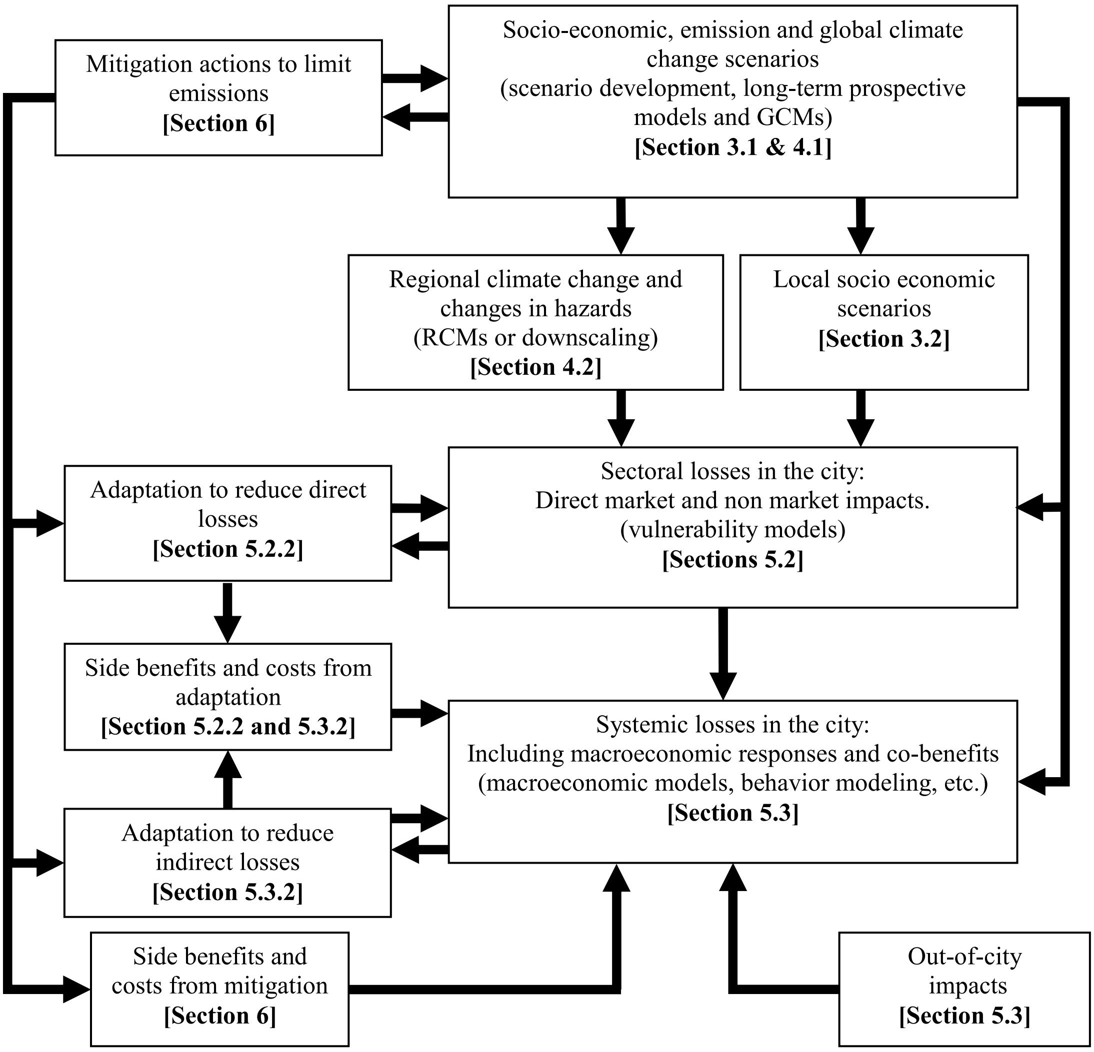
The paper is organised as follows: Section 2 highlights a methodological framework to be used to structure the discussion of key drivers and impact outcomes following a causal chain (see below) starting from global socio-economic development and climate change scenarios and finishing with economic damages at local scale. Section 3 describes global socio-economic and emission scenarios and identifies methods to downscale these scenarios at the city scale. Section 4 describes the global climate scenarios, deduced from global socioeconomic scenarios and summarises existing ways to downscale simulations of global climate change, *i.e.* to translate climate change information at the pertinent scale of analysis. Section 5 assesses how changes in local conditions may translate into economic impacts and the role of adaptation in limiting these impacts. This section takes into account both direct impacts and systemic economic impacts, due to the propagation of direct sectoral losses into the wider economic system. Section 6 assesses the benefits and costs of mitigation strategies, at the local scale. Section 7 concludes from a methodological point of view, and highlights the need for future research.

## 2. A methodological roadmap

This paper proposes a methodological roadmap to assess local economic impacts of climate change. Figure 1 presents the over-arching framework which is interdisciplinary, working across natural science, technology, engineering and economics.

The paper addresses a number of challenges that are unique to climate change impact assessment and some that are unique to the problem of working at local scales. These include the difficulty that climate and weather influence almost all human activities -- from leisure to industrial production -- and the diversity of these activities makes it difficult to assess overall climate change impacts. But even when focusing only on a few activities or impact categories, the task remains problematic because of the wide uncertainties surrounding all the steps of the analysis.

**Figure 1. The different components necessary to assess climate change impacts.**



A first step in impact assessment is to construct a global socio-economic baseline scenario which includes a vision of how different world regions will develop over time, as a function of demographic, economic and technologic trends and of political choices, including climate and mitigation policies. To allow for local impact analysis, especially in cities, it is also necessary to downscale the global socio-economic scenario to describe socio economic conditions at the local scale.

A key challenge is factoring in different views about the future. The future economy that will be impacted by climate change will differ from today's economy, and even small changes in economic development can make a difference in climate change impacts. For example, a reduction in poverty and an improvement in housing quality can reduce vulnerability to climate change (IPCC 2007b, ch7). Impacts will therefore vary with levels and types of economic development as well as with levels and types of climate change. This demonstrates the two-way relationship between development and climate change as does the fact that how cities develop will also determine to some extent emission levels and the nature and pace of climate change in the future.

Future economies are not the only unknown components of the analysis as the future climate is also uncertain. Global emission and climate scenarios can be derived from global socio-economic scenarios but, similarly, climate scenarios are not at a sufficient resolution to carry out local impacts analysis. Downscaling of global or regional climate conditions must be done using statistical relationships or physical methods, which take into account the specificities of the urban context. From this downscaled information, direct sectoral economic impacts of climate change can be estimated in any region and sector. These impacts arise partly from the change in mean climate. Climate change, however, is also likely to increase the risk of certain extreme events. The potential damages from increased severity of extreme climate events are often not included in economic analysis (IPCC, 2007b, ch19). This framework proposes to explicitly take them into account in the assessment of direct climate change impacts.

Even when direct impacts can be estimated with some level of confidence, the indirect effects of this impact on the entire society or economy are more complex to assess. For example, an impact on tourism activities in a city may be foreseen with some certainty, making one important sector of the economy much less profitable than in the past. However, the overall impact on the economy depends on complex interaction of different factors. These include the ability of workers to shift to other economic sectors, the ability of investors and entrepreneurs to create rapidly profitable activities in new sectors, and the ability of the government to facilitate the transitions and support households in difficulty.

The assessment of indirect impacts is particularly important in urban areas. This is because cities concentrate so much activity in limited areas; they function as integrated systems, consisting of many sectors and infrastructures closely interlinked. As an example, many cities are totally dependent on public transportation and the economic activity in London, Paris or New York would be threatened by a long interruption of their subway service. In the same way, damages to the sewage and water drainage infrastructure may lead to serious health issues in cities, with indirect consequences on all activities. As a consequence, assessing climate change impacts in cities cannot be based on quantitative approaches that consider each economic sector separately (Mendelsohn *et al.*, 2000; Nordhaus and Boyer, 2000; Tol, 2002a, b). It requires a systemic view, taking into account all components of the socio-economic activity and the network of relationships making up the system.

Importantly, providing a “best-guess” of future impacts is insufficient to inform public policy and guide adaptation strategies. Climate policy decisions, whether about mitigation or adaptation, need to explicitly take into account uncertainties concerning future climate change (Nicholls and Leatherman, 1996; Fankhauser *et al.*, 1999; Hallegatte, 2008b; Manning et al, 2004). This applies to each step of any assessment of impacts, and especially with respect to the global carbon cycle response to emission scenarios, the climate sensitivity to carbon concentration, the local climate response, and local socioeconomic scenarios (including the influence of policy). Given the extent of uncertainties within each of these factors, it is essential not only to look at median (or “best guess”) scenarios of change but also to look at the most extreme scenarios, even if they have a small likelihood of occurring because they could lead to significant losses and thus may justify specific anticipatory, preventive action. Using an approach to bracket the uncertainty and look at the full range of plausible outcomes to examine the economics of city scale impacts helps to illustrate the link between development and climate mitigation, a cross-scale problem that is not well understood today (IPCC, 2007c, ch12).

Of course, all economic agents will respond to climate impacts by implementing adaptation strategies, therefore reducing damages. Their ability to cope with the new climate, however, is difficult to predict as it depends on the ability to detect a change in climatic conditions in due time, to develop technical or institutional responses to this change, and to implement these responses in an efficient way (Hallegatte, 2007a). Past experience shows that detection failure, mal-adaptation, and over-reactions are common (Tol *et al.*, 1998; Klein, 2001; IPCC, 2007 b ch17). The efficiency of adaptation is then dependent on subtle local factors and several scenarios can be designed depending of this efficiency.

The proposed framework includes assessments of adaptation actions in three cases: (1) a case with no adaptation; (2) a case with an imperfect adaptation, based on observation of current adaptation to climate natural variability; and (3) a case with perfect adaptation, assumed optimally planned and implemented by perfectly rational agents. This approach makes it also possible to assess benefits from global mitigation. It is important to note that, while one can assess the local benefits of local adaptation actions, it is impossible to assess the benefits of local mitigation actions, since local mitigation actions only have a marginal influence on global (or local) climate change. Mitigation results will depend on what is done at the global scale rather than what is done at the local scale.

In an ideal world, adaptation and mitigation costs and benefits would be calculated at the global scale in a unique step through an optimization process (see a very comprehensive analysis of this coupled optimization in Lecocq and Shalizi, 2007 and OECD 2009a forthcoming). However, as mentioned in Lecocq and Shalizi (2007) and Tol (2005), there are key differences in drivers or determinants of mitigation and adaptation potential and decisions. These include different actors, different timescales and often different spatial scales of decision-making. In particular, mitigation does make sense only at the global scale, while adaptation is designed at the local scale and yields local benefits. These differences make it unrealistic to assume coupled optimization of both policies will occur in any one location let alone worldwide. Further, only proactive or anticipatory adaptation, such as, improving adaptation capacity or implementing long-term adaptation policies that have very long timescales, can be designed in conjunction with mitigation policies and strategies, and these represent only a fraction of any aggregate adaptation response. For many adaptation options, decisions about design and implementation will only be made long after initial mitigation choices, when climate actually changes. For these reasons, climate change impact analysis at the local or city scale can consider the global mitigation scenario as an exogenous input.

Finally, as already stated, optimal adaptation is unlikely considering the current barriers to adaptation to climate natural variability that can be observed in many locations. Indeed, looking at risk management in the world today shows that, for many reasons, risk reduction investments are far from optimal (*e.g.*, Nicholls *et al.*, 2007). If, when sea level rises, artificial dikes are not implemented because of misperception of risk or financial constraints or simply bad planning, costs could soar for a significant period of time. Under such assumptions, climate change mitigation benefits would be significant, and disregarding mitigation would lead to a suboptimal situation. On the other hand, assuming perfect adaptation using dikes and land-use planning, flood risks could be controlled in spite of sea level rise, making the benefits from mitigation much lower. So, the best decision on mitigation depends on whether we assume a theoretical world of perfect adaptation, no adaptation or a world that resemble the current one with some imperfect level of adaptation.

This is why city scale impact assessment should take into account the interactions between imperfect (sub-optimal) mitigation and adaptation strategies. For practical purposes, analysis of climate policy benefits can be carried out in three distinct steps. First, an assumption has to be made on the response of physical systems to human interferences (*e.g.*, climate sensitivity). Second, an assumption is made about the level and timing of global scale mitigation over the coming decades to century, thus determining climate stabilisation outcomes in the long term.[8] Third, we account for the innumerable decisions that will be made by individuals and businesses in the nearer term and throughout this century about local, regional and sector-specific adaptation presumably on the basis of increasing knowledge about climate change. In this methodology (see Figure 2), we suggest that mitigation benefits can be assessed

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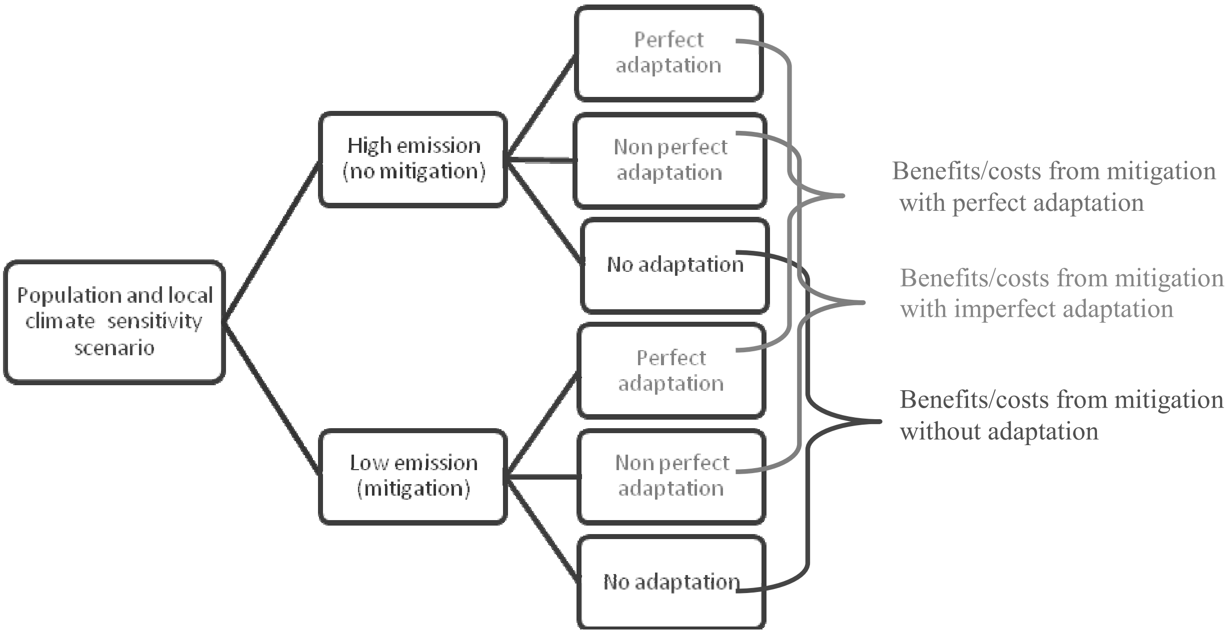
[8] Of course there is clearly a difference between a decision on long-term climate change goals at the global scale and the actual delivery of some level of mitigation which when combined with other investment and development decisions will determine actual emission levels. The implementation of mitigation actions will undoubtedly also be local, decentralized – comprised of many individual decisions -- and proceed in parallel with adaptation. But for the purposes of modelling impacts it is necessary to simplify this situation.

across the three distinct adaptation scenarios proposed above, which represent a continuum of different possibilities: no adaptation, imperfect adaptation (inspired by observations of the current situation), perfect adaptation. The no-adaptation and perfect-adaptation cases bracket possible outcomes; the scenario inspired from the current observation provides an idea of climate change costs if the world capacity to manage risks does not change significantly in the future.

**Figure 2. Assessing the benefits from mitigation**



Also, unlike global scale analyses (*e.g*. IPCC, 2007b, ch18; OECD 2008b; ENV/EPOC/GSP(2008)17), urban case studies allow us to use local impacts as a window through which we can consider the interface between global mitigation and local adaptation. Indeed, global mitigation objectives imply some consistency between local adaptation and mitigation measures. This is especially true in cities, where local mitigation and adaptation use the same policy levers (*e.g*., urban planning building standards). Working at urban scale also allows researchers to account for important local contextual issues in policy analysis (*e.g*., the influence of local geographies and development patterns on impacts; or the distribution of institutional authority between local and national actors in key sectors affected by climate change).

The remainder of this concept paper describes and discusses in more detail the main methodological steps required to carry out a local assessment of the economic impacts of climate change.

## 3. From global to local socio-economic scenarios

A first step in carrying out an impact assessment is the development or the choice of a baseline (or control) scenario, *i.e.* a scenario in which no climate change policy is included. Such scenarios have been developed, for example, by the OECD (*e.g*. OECD, 2008) and by the Intergovernmental Panel on Climate Change (IPCC), in the Special Report on Emission Scenarios (SRES, Nakicenovic and Swart, 2000). The numerous scenarios describe the world evolution in terms of demography, technology and economy, with different assumptions about, for instance, how the world becomes more globalised or remains regionalised or how economic development focuses on industrial production. These scenarios are developed in two stages: first, qualitative storylines describe how the world can evolve (*e.g*., becomes more globalised or more regionalised; becomes more or less oriented toward fossil fuels); second, economic-technology models are used to translate these qualitative storylines into quantitative scenarios that include, among other characteristics of the economy, GDP, future technologies and energy prices. These scenarios, however, are at a very low spatial resolution, considering only large regions (*e.g*., Europe, Africa).

These baseline scenarios are not supposed to be predictions of the future. Moreover, it is impossible to attribute probabilities to each of these scenarios as it is impossible to make predictions about the choices that will be made and then on world evolution (even in a probabilistic manner). These scenarios, instead, are developed to represent a range of possible and consistent futures and it is assumed that investigating climate change in each of these baseline scenarios would provide an unbiased estimate of future climate change risks.

Global scenarios often have world region (multi-country) detail but are not at a resolution that would permit local impact analysis. Hurricane damages, for instance, depend upon building standards, population and exposure in coastal areas. This information is not available in scenarios developed at the global scale.

As a result, local impact assessment requires *socio-economic downscaling*, *i.e.* the development of a local scenario that describes the socio-economic conditions at a pertinent scale. As projecting social and economic trends is difficult, one possibility is to consider the current society and economy and to assess the impact the future climate would have on current cities (*e.g.* see Nicholls *et al.,* 2008). The advantage of this method is to control uncertainty and reduce the number of unknown parameters in the analysis. However, this approach is not always acceptable, especially in developing countries, where changes in exposure and vulnerability over time can be very large. This is especially true where (i) the urbanisation rate is increasing very rapidly with the shift from primary to other economic sectors and the migration of population from villages and rural areas toward the largest cities; (ii) the improvement in the standards of living (especially for housing quality) limits damages due to extreme weather; (iii) governments and local institutions become more able to implement mitigation policies and emergency measures.

Ideally it would be possible to develop a vision of the local socio-economic future in collaboration with local stakeholders (OECD 2009b forthcoming). Some examples exist, for instance in the UK where downscaling of IPCC global SRES scenarios has been carried out for national and local assessment purposes (*e.g*., in the U.K by the Office of Science and Technology, 2002; McKenzie-Hedger *et al.,* 2006). Scenarios of city development are developed in many cities, to help design urbanisation plans and land-use regulations. A number of models have been developed to simulate urban development (see, *e.g*., Wegener, 1994; EPA, 2000; Lefevre, 2005), however, they usually consider time horizons of less than 30 years. Urban scenarios with a 2100 time horizon are not generally available so far, yet such scenarios would be of relevance to the understanding of urban development and its interface with global climate change.

To develop long term-urban scenarios, it is possible to begin with global scenarios and layer in a number of “local perspectives” about key issues including:

- How will urbanisation rates evolve in developing countries? In particular, the question is whether, with economic growth, developing countries will converge to developed countries’ urbanisation rates, which are frequently higher than 80%, or whether they will converge to a different end-point.

- How will additional urbanisation in the country or region be distributed among cities? In particular, the question is to whether, in future, city sizes will saturate at some level or whether they will keep growing. For instance, assuming that the Indian urbanisation rate will rise from 30% today to 65% in 2080 and that all Indian cities will grow at the same rate, Mumbai would have 60 million inhabitants in 2080. It is unclear if a city with this number of inhabitants is viable, for example whether there is sufficient land and resources in the Mumbai region to support such a large population. One possibility is that negative externalities (*e.g.* congestion and local pollution) will exceed the positive externalities of agglomeration (*e.g.* availability of workers, firm network externalities) and represent a strong obstacle to the development of such cities.

- How will sub-regional population and economic growth differ within a country or a region? For example will coastal cities grow more rapidly than inland cities?

- How will economic development in cities differ from economic development in the rest of the country/region? Today, cities are wealthier than rural areas and they are growing more rapidly, but this trend could change in the future. Also, the economic structure will evolve differently in cities than in the rest of the country, *e.g.* with services growing more rapidly than other sectors.

- How will urban spatial planning and architecture evolve in the future? For instance, additional urban development can be done through low-density suburban development or through high-density urbanisation. Future streets can be narrower or wider than today; new materials can be used in streets and buildings, absorbing more or less solar energy; more parks can be introduced in cities. Depending on these urbanisation characteristics, energy consumption, and the exposure and vulnerability to heat waves and floods may differ significantly.

- How can infrastructure development keep pace with growing population? For instance, sewage and water treatment infrastructure are underdeveloped in many cities of the developing world (*e.g.* the Camdessus Report on Water Infrastructure, 2003). The development and the characteristics of future infrastructure will play a major role in city vulnerability to climate change. For instance vulnerability to increased flood incidence will depend on whether sewage and drainage systems are able to cope and on whether urban transport is based on roads and individual cars or on public transportation (*e.g.* subway).

- In coastal cities, vulnerability to coastal floods and storm surges will depend on human-induced subsidence that, in turn, depends in part on where the water consumed in the city is extracted from. If ground water is pumped in the city, subsidence rates increase and amplify global sea level rise. Subsidence will depend on choices made by city planners. For instance, the city of Shanghai has invested in systems to stop pumping ground water, thereby reducing human-induced subsidence.[9] Assessing coastal flood vulnerability thus requires a scenario for local ground water use and subsidence.

While socio-economic scenario development is complex, their construction at local scale is both a necessary input and an essential part of any local climate impact and policy assessment and they thus require research attention. Moreover, the fact that future impacts depend on these factors makes it possible to use them as policy levers to reduce future climate change vulnerability and increase resilience.

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[9] However it should be noted that better regulation of the use of groundwater may not be the only factor driving human-induced subsidence. In the case of Shanghai, the weight of skyscraper buildings which have been built up over time also seem to have been an important driver of subsidence.

## 4. From global to local climate change

Global emission scenarios for all greenhouse gases (GHG) are derived from global socio-economic scenarios. From GHG emissions, carbon cycle and climate models (or Atmosphere-Ocean General Circulation Models, referred to as GCMs) produce climate scenarios, that contain projections of key meteorological variables (temperature, precipitation, wind, pressure, sea level, etc.). These are typically available at a low level of spatial resolution (*i.e.* not more than 100km by 100km).

There are significant uncertainties in climate scenarios. For instance, the IPCC Fourth Assessment estimates the "likely" range of climate sensitivity, which is the increase in mean global temperature for a doubling of $CO_2$ concentration above pre-industrial levels, to be from 1.5 to 4.5°C with a best guess of 3°C (IPCC 2007a). Despite these uncertainties, the models broadly agree across a range of possible climate sensitivities and other key patterns of climate change to show more warming at higher latitudes and across continental land mass, more precipitation in the tropics and at high latitudes, and less precipitation in mid-latitude regions (IPCC 2007a and IPCC 2007b).

As far as sea level rise is concerned, the IPCC indicates that, by 2100, mean sea level will have risen by 18 to 38 cm in the SRES/B1 scenario, and by 26 to 59 cm in the SRES/A1F1 scenario[10]. On the other hand, Rahmstorf *et al.* (2007) project that an A1FI-like scenario would lead to a best-guess SLR of 100 cm, while a B1-like scenario would lead to a 70 cm SLR. The difference stems from the fact that IPCC projections do not include all possible contributions from melting ice sheets (due to the limitations of the modelling techniques used) whereas Rahmstorf (2007) uses a different technique to estimate future sea level change. This technique uses the observed relationship between global sea levels and temperature to project future sea levels from temperature projections. While the Rahmstorf technique is likely to be too simplistic, its advantage is that it uses real data and avoids many of the uncertainties introduced by global climate models. The difference between the two assessments is very significant and has implications for policy.[11] In all cases it is useful to consider in a systematic manner both optimistic and pessimistic scenarios in order to bracket the uncertainties and provide unbiased analysis for decision-makers.

To assess climate change impacts, one usually starts from one or several socio-economic scenarios and uses one or several GCMs to create "climate scenarios", *i.e.* low-resolution global simulations of climate change. The low spatial resolution is sometimes good enough to carry out impact analyses, *e.g.* to assess the impact on agriculture or forestry. Quite often, however, climate impacts will strongly depend on the precise local change in climate and a higher resolution is needed. In cities local climate is particularly important because of their micro-climates including the urban heat island (UHI) effect (Oke, 1987). An UHI refers to temperatures that are often warmer downtown in comparison with the outskirts of the city. The temperature differences can reach up to ten degrees C for large urban agglomerations and can strongly amplify heat stress, especially at night during heat waves, which in turn can lead to serious consequences in terms of public health. This was the case in 2003 when a strong heat wave occurred in Europe and caused more than 70 000 casualties with higher percentage of victims in urban areas for example in France (Evin *et al.*, 2004; Rousseau, 2005). In such a situation, it is necessary to downscale GCM output, to take into account high resolution processes, and produce climate scenarios at a resolution that is high enough to be used in impact models and analysis.

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[10] It is important to mention that sea level rise will be heterogeneous, with locations experiencing more or less rise in local sea level. These local variations arise from changes in atmospheric and ocean circulations, in addition to geological uplift or subsidence.

[11] For a discussion of these policy issues, see, *e.g.*, Hansen, (2007); Oppenheimer *et al.*, (2007). Also as part of this OECD work stream, see discussion of these issues in a global port cities flood exposure assessment by Nicholls *et al.,* (2007) and a case study on Copenhagen in Hallegatte *et al.*, (2008c).

Some sort of downscaling is also needed when the phenomena that one wants to consider are too small to be adequately reproduced by GCMs. Examples of such phenomena can be heavy precipitation that has a spatial scale of the order of a few kilometres or tropical cyclones. Tropical cyclones cannot be reproduced by GCM because their intensity depends on small-scale processes around the eye that a 100km-resolution model cannot resolve.

There are two ways of downscaling: using statistical methods or physical models.

### *4.1 Statistical methods*

The first method uses statistical relationships, calibrated on historical data, to relate large-scale drivers – which GCMs can reproduce – to local phenomena – which GCMs cannot reproduce. Even though our knowledge of the laws of physics helps selecting potential predictors, this method is not directly based on physical laws. For example, Franco and Sanstad (2007) rely upon statistically downscaled large-scale temperature change estimates in California to develop individual city-level temperatures using historical relationships. A calibrated statistical relationship is the easiest way of representing UHI without explicitly modelling highly-complex small-scale weather processes.

Another example of this method applied to hurricanes is provided by Elsner and Jagger (2006), who estimate the return level of (small-scale) extreme hurricane wind on the U.S. coastline, as a function of global climate indices like ENSO and NAO, which can be represented by GCMs.

Such statistical methods are computationally efficient and have often a good skill in the current climate. Statistical models, however, have two main drawbacks: first, they need long series of reliable data; second, it is difficult to know the validity domain of statistical relationships. A statistical relationship between large-scale climate indices and small-scale variables, indeed, can be different in a different climate. For instance, the correlation between sea surface temperature and hurricane intensity is very strong in the present climate (see, *e.g.*, Emanuel, 2005), but it does not mean that if the global climate warms by 2°C , hurricane intensity will automatically increase: the effect of a local or temporary perturbation may be different from the effect of a global or permanent change.

Also, if UHI is modelled with a statistical relationship calibrated on historical situations with large-scale temperatures that lie between 10 and 30°C, it is impossible to tell if the relationship remains valid when large-scale temperature exceeds 30°C. This situation will, however, arise when using this relationship to assess climate change impacts. Even more problematic, city infrastructure will change in the future: new buildings will be built, new neighbourhood will be developed, new parks will be introduced, and air-conditioning equipment will be installed. These new developments may modify the statistical link between large-scale climate indices and small-scale conditions. Statistical relationships, therefore, must be used with care, if possible in the situation where conditions will not change too much.

### *4.2 Physical models*

To avoid the problem of validity of historical relationships, one may use physical models, which are based on physical laws and mechanism-based modelling. Physical models are considered of particular interest when investigating extreme patterns and variability changes. Of course, physical models often require calibration, so that the distinction between physical models and statistical models is sometimes fuzzy.

These physical models, used to downscale GCM output, can be Regional Climate Models (RCM) that take as input a large-scale forcing produced by GCM (see examples of this approach in Christensen and Christensen, 2007), or specific models like hurricane models.

For instance, Christensen and Christensen (2007) summarise the finding of the PRUDENCE project, which is based on this approach: a few GCMs were used to produce scenarios of global climate change at low resolution (about 200 km), and several RCM were then used to downscale these findings and produce climate change scenarios over Europe, at a resolution that allows impact analysis (about 50 km). A series of impact studies was then proposed on, for example, extreme events (Beniston *et al.*, 2007), hydrological impacts (Graham *et al.*, 2007), agriculture (Olesen *et al.*, 2007). A follow-up project, ENSEMBLES, is now applying the same approach with the next generation models that have a resolution of 25 km or less.

To account for the specifics of urban areas, a 50 or even 25 km resolution is not enough and a better resolution is required to reproduce the UHI effect. To do so, specific urban models have been developed, with very high resolution and specific modules to take into account characteristics of urban land cover. For instance, the Town Energy Balance (TEB) (Masson 2000) is a model that reproduce the energy fluxes in urban environments and that can be included in the high-resolution atmospheric model Meso-NH (with resolution of up to 250m) that is, therefore, able to represent all aspects of the urban meteorology, including all kinds of land covers: natural soils, vegetation, water, and built-up areas. Numerous simulations can then be conducted for various urban environments and various conditions (*e.g*., Lemonsu *et al.,* 2002, Pigeon *et al.*, 2006; Pigeon *et al.,* 2008), to assess how large-scale climate conditions and local urbanism interact to create urban micro-climates.

These models have been used to get a better understanding of urban meteorology, but their application to climate change issues is still experimental. Only these models, however, would be able to predict the impact of higher global or regional temperature changes on street- or building-temperatures in cities, and to assess the effectiveness of adaptation measures like changes in building materials.

Another example of the use of physical models to downscale global climate scenarios deals with hurricanes. Here, two approaches have been used. First, high-resolution RCMs have been used to assess how hurricanes could be modified by global climate change (*e.g*., Knutson and Tuleya, 2004; Knutson *et al.*, 2008). This approach projects limited changes to hurricane characteristics, with an increase in maximum intensity and rainfall, and a decrease in frequency. This approach suggests, therefore, that climate change should not increase hurricane risks in a significant manner. Second, Emanuel (2006) uses a hurricane model that takes as input large-scale conditions (wind patterns, thermodynamic conditions, etc.), and provides statistics on hurricane tracks and intensity. Using this model, Emanuel investigates the changes in hurricane risk due to a 10-percent increase in potential intensity (caused by an increased sea surface temperature by approximately 2°C). In Hallegatte (2007a), the model is then used to assess how an increase in potential intensity could modify the annual probability of hurricane landfall on the U.S. Atlantic and Gulf coastline. According to this analysis, the probability of category-5 hurricane landfall on the U.S. Atlantic and Gulf coastline would be multiplied by 3, suggesting the possibility of a large increase in hurricane risks in the North Atlantic basin. The most recent analysis by Emanuel *et al.* (2008) expands this approach to account for additional changes in climate (*e.g*., change in wind patterns) and carry out the same analysis with 7 different climate models. It concludes that climate change could modify very significantly hurricane risks, although the sign and magnitude of the changes vary from basin to basin and from model to model, reflecting large differences in model projections at the regional scale.

These kinds of results in terms of local weather change or of weather hazards are useful for engineers, architects, urban planners, water managers, risk managers, and many other practitioners. They do not indicate anything however, about the economic and societal impact of such a change. To investigate this question, it is necessary to move from estimates of changes in local conditions and hazards to direct economic and societal losses – expressed in monetary units or in other non-monetary units (loss of lives, mortality and morbidity indices, etc.).

# 5. From local scenarios to physical and economic impacts

## *5.1 Overview impacts at the city scale*

Climate change will have physical and economic consequences across numerous and diverse human activities (Table 1). These consequences can be classified into two broad categories: market impacts, which directly affect the economy (*e.g.*, asset losses due to sea level rise) and non-market impacts, which affect humans and the environment in a broad way (*e.g.*, health, biodiversity). Climate change impacts can also be classified across the dimensions of direct and indirect consequences. Within direct consequences they will result from changes in the mean climate and from changes in extreme climate (also referred to as climate variability as opposed to climate means). While emerging from the broader literature on climate change impacts more generally (*e.g.* see IPCC 2007b), this structure for addressing climate change impacts is also consistent with and can be used to help think about impacts at city-scale.

**Table 1. Types of impacts with a few examples of impacts in cities.**

| Impacts | Direct | | | Indirect |
|---|---|---|---|---|
| | Climate mean changes | Climate variability changes | Catastrophic changes | |
| Market | Decreased/Increased energy consumption due to heating/cooling demand<br>Rise/Fall in tourism due to higher temperature<br>Asset losses due to mean sea level rise (V) | Asset losses due to hurricanes or storm surges (V) | Major asset losses due to catastrophic sea level rise | Effect of the decline in tourism on the city economy.<br>Fall in worker productivity because of health problems<br>Spatial or sectoral diffusion of economic losses into the wider economic system (*e.g.* through disruptions of lifeline services, following a storm surge) (V)<br>Effects on long-term economic development |
| Non market | Increased mortality and morbidity from, *e.g.*, development of vector borne diseases due to increase in global mean temperature<br>Loss in thermal comfort in the city.<br>Population at risk because of sea level rise (Q) | Number of deaths because of more frequent heat wave and thermal stress.<br>Population at risk in coastal cities because of increased storminess (Q) | Cultural losses and migration, including ethical aspects induced by catastrophic sea level rise | Effect of climate change induced water shortages on mortality and morbidity<br>Inequality deepening; loss of human security and inter/intra state conflict |

Notes: V = valuation in monetary terms; Q = quantitative metric but not in physical rather than monetary terms.

Direct market impacts are only a fraction of total economic costs due to climate change physical impacts. Direct costs or losses directly arise from climate change physical impacts. For instance, because of sea level rise or after a coastal storm, direct costs or losses include the costs of replacing or repairing damaged buildings. Indirect costs represent then the way direct costs become magnified[12] when working through the wider economic system in a regional or even national context, for example, through changes in the form of economic production, through job gains or losses in the reconstruction period, and other short- and long-term effects on growth and investment.

Within direct impacts, the climate change driver may be changes in average conditions (*e.g.* temperature or precipitation or sea level) or extreme changes (*e.g.* storm surges, maximum or minimum temperatures, and extreme precipitation). The assessment of economic impacts is complicated by the relative difficulty of predicting extreme change with confidence. Mean climate change can be predicted with relative confidence and the direction of mean change across at least two climate variables (temperature, sea level rise) is widely accepted in the scientific literature[13]. It is also widely accepted that mean change can entail economic effects such as increase in average demand for electricity in some regions due to cooling needs, or asset losses due to mean sea level rise. On the other hand, changes in extreme values and in the frequency of extreme values are more uncertain and can entail potential extreme physical impacts, such as high mortality and blackouts during heat wave or destruction of the transportation infrastructures because of hurricanes. Mean and extreme impacts should be distinguished in part because their prediction requires different methodologies, but also because they will demand different types of adaptation strategies. A third important driver is catastrophic or non-linear climate change. While relevant to impact and climate policies assessment (see IPCC 2007b; Alley 2005), it is not possible to predict catastrophic change with any certainty as it is thought to revolve around major thresholds or tipping points where a small change in one or a combination of climate variables may result in a large change in other parts of the Earth's bio-geophysical system (*e.g.* in ocean currents or in ice sheet dynamics) (Schellenhuber *et al.*; Kelly *et al.*; OECD 2007). Large physical and economic impacts could arise from these major climate discontinuities or irreversibilities, however, because they are impossible to predict at global (or local) scale, this last type of impact is not covered in this study.

Market impacts are those for which market prices exist and allow for an uncontroversial assessment of monetary values. For instance, if higher temperatures lead to an increase in air-conditioning energy consumption, this impact can be valued as the product of the energy price by the amount of additional energy consumption. The fact that valuation is non-controversial does not mean that this assessment is easy, as will be shown later. But it means that assessment problems are mainly in the technical domain, not in the ethical domain.

Non market impacts include impacts that are not easily quantifiable in monetary or other economic units. These include principally human health and ecosystem impacts of climate change. For example, converting the number of extra deaths from climate change into monetary units, such as GDP percentage points, raises ethical issues as well as methodological issues (see Box 1). For instance, there is always a controversy about the validity of any valuation of health effects (for a discussion, see Grubb *et al.,* 1999). Quantification in monetary terms is nevertheless necessary to fully integrate the consideration of health impacts into any comprehensive economic assessment or modelling exercise that treats both the costs and benefits of policies.

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[12] In most of the cases, the diffusion of direct costs across the wider economic system increases the total cost, by adding indirect costs. It happens, however, that the diffusion of direct costs entails indirect gains.

[13] As far as precipitations are concerned, for some regions the projected changes are likely or very likely whereas for other regions, confidence in projected change remains weak (see IPCC, 2007a)

**Box 1. Valuation of human life: some methodological issues**

To encompass non-market health impacts, many studies use the Value of a Statistical Life (VSL). A VSL can be estimated from evidence on market choices that involve implicit tradeoffs between risk and money, such as smoking a cigarette or driving a car (Viscusi *et al.*, 2003). They can also be estimated based on stated preferences (*e.g.* from consumer surveys of the willingness to pay to avoid risks to human life). Meta-analyses of studies suggest that estimates of VSL may depend on the age, income, gender, education, health (etc) of the respondents, and on the risk change context, as well as the estimation method used (Viscusi *et al.*, 2003). Viscusi et al (2003) note that even though values depends on the context, *e.g.* type of risk and the probability of occurrence of the considered event, most estimates lie between $1 million and $10 million in the U.S. The VSL meets serious ethical challenges, including the difference in VSL between rich and poor individuals and the possible difference between individual choices (used to assess VSL) and collective choices (for which VSL are used).

The World Bank and the World Health Organisation sometimes choose to use physical indicators of risks to human life such as the "Disability-Adjusted Life Years" (DALYs), to quantify health effects (see Murray *et al.*, 1996). These indicators can be somewhat less controversial and as a complement to more formal economic impact assessment which otherwise requires valuation of all direct impacts. On the other hand, they do not allow a direct comparison of costs and benefits of a policy in common unit, and can hence *e.g.* not indicate if a policy measure ought to be implemented or not. The DALYs concept uses life years lost due to premature death and fraction of years of healthy life lost as a result of illness or disability to measure the burden of disease. Contrary to the VSL, age is taken into account in the DALY, through weights that are incorporated to discount year of life lost at different ages.

An alternative to this monetary aggregation of damages costs is the use of numeraires to describe climate change impacts across several dimensions. For instance, in part to take account of non-market risks of climate change in any assessment, Schneider *et al.*, 2000 suggest the use of five "*numeraires,*" as the best compromise between accuracy and relevance of information about impacts (physical and monetary). The objective of this set of numeraires is to provide decision-makers with all relevant information, without obscuring relevant trade-offs through monetary aggregation and normative decisions about valuation. They argue that relying uniquely on monetary metrics necessarily omits certain types of impacts or hides strong value judgments on which a range of legitimate opinions exist.

Instead they propose the use of the following numeraires:

- A monetary assessment of impacts on market-based activities and human settlements.
- The number of lives at risk and health risks.
- A quality of life index, including psychological dimensions such as having to migrate, the loss of landscapes with their cultural value, etc…
- A measure of the risks to ecosystems, and of the biodiversity losses.
- An indicator of the distribution of risks among different populations and the impacts on inequalities.

A sixth numeraire may also be relevant, namely the security aspects of climate change impacts. Recent literature (*e.g.* see a review in Gledistch 2007; Barnett ; Watkiss & Downing ; Watkiss & Hunt), has proposed that climate change impact assessment include understanding of its effects on individual and international security (UNDP, 1994; Mack, 2005). Individual security would include violence to individuals inside countries, access to basic resources (food, water), and "protection from sudden and hurtful disruptions in the patterns of daily life" (UNDP, 1994). Changes in extreme weather events and natural disasters caused by climate change (IPCC, 2007a) may affect both individual and international security as it could entail political instability, civil unrest, international conflicts and migration (see Suhrke, 1997; Homer-Dixon, 1999; Gleditsch, 2007). A number of studies recognise in particular forced migration due to climate-change as a possible source of future conflict (see Saleyan and Gleditsch, 2006; Gleditsch *et al.*, 2007). Including security aspects would usefully complement the other indicators as it provides a numeraire to consider an important aspect of extreme event consequences.

There are also several limitations to the use of multiple numeraires, which prevent analysts from operationalising this approach today. For instance, there is no agreement even amongst experts on how to measure risks to ecosystems or biodiversity losses let alone the climate change driven portion of such change. Further, the use of different types of numeraires provides a rich range of information for use by decision-makers but only monetised impact information can be used in many economic models used for policy analysis. Nevertheless where non-monetary metrics are available for assessing change across this range of issues it is important to report these. Systematically using such a set of six numeraires would allow analysts to incorporate the latest findings from the (physical) impacts of climate change, without being paralysed by the controversies raised by the monetary valuation of non-market impacts. Even if this information is ignored in modelling of economic impacts it may be useful to complement such analyses to inform policy decisions

In the context of the OECD work on cities and climate change (Nicholls *et al.,* 2007; Hallegatte *et al.*, 2008c), a number of the impact areas laid out in Table 1 are included through the use of monetary or other quantitative metrics. In Table 1, those impacts valued in monetary terms are marked with a (V); these include mostly direct and indirect market impacts. Some non market impacts, such as the population at risk of coastal flood, will also be quantified (Q), *i.e.* they are expressed in physical terms, but not valued. This includes the reporting of risks to people and assets (*i.e.* flood risk) through the use of physical metrics such as "number of people at risk of flooding" and "size of land area" at risk. In the analyses conducted under the project, there is no attempt to monetise health risks. The first step in the assessment of the total economic cost is to convert local climate change into physical impacts and direct losses in each sector, expressed in monetary or non monetary units.

## *5.2 From local scenarios to physical impacts and direct sectoral losses*

### *5.2.1 Assessing physical impacts and direct sectoral losses*

This section assesses how changes in climate conditions and hazards could translate, for a given local socio-economic scenario, into changes in "sectoral losses", *i.e.* in economic losses in one sector, expressed in monetary units or other physical impacts, expressed in non monetary units. Practically, there are two methods to translate climate conditions into direct losses. The first one is based on physical models, while the second one is purely statistical.

An example of a physical impact model can be found in the energy sector. For instance, economic losses due to an increase in electricity needs can be assessed at the building scale, using the properties of building insulating materials in various temperature ranges. The insulating properties of the buildings affect cooling and heating demand and thus energy spending (Crausse and Bacon, 2007). This kind of model allows linking changes in temperature to economic losses through increase energy consumption.

In the case of flood or storms, physical impact models have been developed to advise public policy and help the insurance industry assess its level of risk. An example of these models is the HAZUS model (see Scawthorn *et al.*, 2006). These models are based: (i) on a comprehensive dataset of the *exposure*, *i.e.* the characteristics and value of the property exposed to a hazard at a fine spatial resolution; and (ii) on vulnerability models, which relate wind speed, flooding depth and any other physical description of a disaster, to a damage ratio, which is the share of the exposure that is destroyed or damaged for a given hazard level. These models describe a hurricane by its wind field and storm surge and estimate damages to properties. The drawback of these models is the amount of data they require – this information is for instance not available for developing countries – and the fact that it is particularly difficult to create scenarios to project exposure over long timescales.

Statistical models, on the other hand, can be very simple. They are usually based on historical relationships between climate and activity in a given sector. For instance, several studies focus on the statistical relationship between health and climate change. Climate change health impacts can come from vector-borne diseases, Martens *et al.,* (1997), thermal stress, Dessai (2003), or ozone concentration, Bell *et al.,* (2007). In these studies, the authors evaluate the relationship between current average temperatures and health changes based on historical data. They combine then their results with climate scenarios to evaluate the impacts of climate change on health.

Statistical models have also been used to determine the impact of an increase in temperature on energy consumption in cities, through demand for cooling associated with high temperature. To do so, it is necessary to use historical data or to find regions which are analogue to the expected future city which is considered (see, *e.g*., Hallegatte *et al.*, 2007a). For instance, to quantify the effect of extreme heat periods in California, which are projected to become longer, more frequent and more intense because of climate change, Miller *et al.* (2007) calculate a temperature-electricity demand relationship thanks to historical data. This relationship summarises the link between large-scale temperature and city-scale temperature (including the effect of UHI) and the link between city-scale temperature and electricity demand. This relationship, therefore, is both a climate downscaling and an impact assessment. In general, using such statistical relationships, it is found that in places where temperatures are currently low in winter (*e.g*., Quebec see Lafrance *et al.*), climate change will reduce energy demand, at least for small increase in global temperature whereas in places where temperatures are already high (*e.g*., California), even modest climate changes would increase energy demand.

Statistical models can also be used to find the relationship between temperature and tourism, and to assess the direct losses (gains) due to the global warming induced decline (increase) in tourism, see Hamilton *et al.* (2005).

In the case of hurricanes, studies have been based on the use of past hurricanes, and data on the resulting direct economic losses to create statistical relationships able to predict future damages (Howard *et al.*, 1972; Nordhaus, 2006; Hallegatte, 2007a; Sachs, 2007; Schmidt *et al.*, 2008). In most cases, the authors assume that the losses due to a hurricane making landfall depend upon the hurricane intensity and local vulnerability parameters that depend on time and location (or, possibly, on population, wealth, or assets). They calibrate then a statistical function on past hurricanes and use this function to produce an estimate of how a change in hurricane intensity or frequency would translate in terms of direct losses. This method was used by Hallegatte (2007a) to assess the change in landfall probabilities projected by the Emanuel (2006) model in response to a 10-percent increase in potential intensity, suggesting that annual mean hurricane losses in the U.S. could increase by 50 percent (from $8 to $12 billion per year) in response to this change.

Of course, using statistical models leads to specific problems. If the relationship between temperature and energy consumption is only calibrated on historical data, it cannot take into account future changes that go beyond historical values nor any change in vulnerability (*e.g*., due to changes in heating technologies, in air-conditioning equipment rate, or in habits). In the same way, if hurricane losses are assessed using a statistical relationship, changes in building norms are difficult to take into account.

In these studies, the three first numeraires of Section 5.1, namely market impacts, number of lives at risk and health risks, and quality of life, are often the only impacts to be assessed. Other types of impacts (on biodiversity, inequality, and security) are much less studied. Today, however, more research is carried out on urban biodiversity and climate change (see, *e.g.*, Grimm *et al.*, 2006) and progress can be expected soon in this dimension. Also, it has been suggested for a long time that climate change is likely to increase global inequalities (*e.g.* Tol *et al.*, 2004). Less has been done on local inequalities (IPCC 2007b, ch7). The landfall of Katrina on New Orleans has renewed attention on the larger weather vulnerability of the poorest communities within a country, and on the inequality-widening effect of disasters (*e.g.* Atkins and Moy, 2005; Tierney, 2006). Finally, long-term local security aspects (*e.g.*, food security, individual security, civil unrest) have also been highlighted by the Katrina landfall, with, for instance, a 70% increase in crime rate between the pre- and post-Katrina periods (see Van Landingham, 2007).

### *5.2.2 Adaptation to direct losses*

The link between weather variables and sectoral losses is not constant over time, however. This link can be modified through risk management and adaptation strategies that need to be taken into account in the analysis. It seems impossible, indeed, that no adaptation actions will be undertaken in the future. In the case of hurricanes, for instance, numerous actions have already been undertaken in the last one hundred years to reduce hurricane damages and these actions demonstrate that adaptation can be effective. First, investments in new protection infrastructures like flood protection systems or dams and building elevations have been done. Second, building codes have been improved and they have limited hurricane damages. Also, existing norms have been enforced more rigorously, since hurricanes have shown that the lack of compliance with existing rules had significantly increased damages. Third, hurricane track forecasts have improved and better warning systems have been implemented to help people and business to prepare for hurricane landfalls and avoid damages. Thanks to early warning, people and businesses can protect houses and suspend dangerous industrial processes, which in turn reduce damages.

Adaptation strategies to reduce health impacts have also already been observed. As stated in Kirshen *et al.* (2004), people who live in climates with extreme heat or cold periods have already found ways to reduce exposure by moving directly (*e.g.*, by car) from one cooled (or heated) space to another. In their Boston case study, Kirshen *et al.* find that improvements in heat wave resilience have already been significant in the last two decades, thanks to better forecasts, regular weather warning and improvements in the health care system.

Many options to cope with climate change in various sectors have been evaluated in the literature. For instance, adaptation options and their costs have been assessed for coastal zones and sea level rise (*e.g.*, Tol, 2002a&b; Nicholls and Tol; 2006; Bosello *et al.*, 2007), for the agriculture sector (*e.g.*, Rosenzweig and Parry, 1994; Reilly *et al.*, 2001; Butt *et al.*, 2005); for the water sector (*e.g.*, Dore and Burton, 2001; Callaway *et al.*, 2006; Kirshen, 2007); and for the energy sector (Morrison and Mendelsohn, 1999; Mendelsohn, 2003). But few studies have considered the special case of urban areas, which require some specific consideration and analytical approaches.[14]

To cope with increased water demand in urban areas, for instance, improved water supply infrastructures will be needed in developed and developing countries alike. But crisis or disaster management will also be necessary. In Spain, adaptation strategies are currently being developed to determine emergency protocols when facing drought and scarcity episodes. These plans include, for example, specific measures to be taken for urban supply, and defining priorities for water use in the case of shortage (see EEA, 2007). In the case of Mexico city, the entire current hydraulic system may have to be

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[14] There are however a limited number of studies which offer a range of insights. For a recent review, see Hunt and Watkiss, 2007.

modified, since currently nearly all waste and storm water is pumped out of the valley while drinking water must be brought in over long distances, entailing high transportation costs. This system could easily be improved, and such an improvement being an obvious first step in climate change adaptation (see Connoly, 1999).

One specific obstacle for adaptation in urban area is that structural modifications in cities are very costly and occur slowly, over a long time horizon (Grazi *et al.,* 2008). For instance, urban planning and land-use management are very efficient ways to reduce hurricane risks (Burby and Dalton, 1994), but buildings have very long lifetime and urban planning can reduce risks only over several decades. In most parts of Europe, city structures have been created over centuries (Grazi and van den Bergh, 2008) and an urban building has a lifetime of 50 to more than 100 years (Balaras *et al.*, 2007). As a consequence, urban adaptation options often must be anticipated by at least decades to be effective. But, so far, there is no clear idea about what exactly must be done to reduce climate change impacts. For instance, to Kirshen *et al.* (2004), future adaptation in Boston could include the use of shade trees and alternative building materials to reduce albedo and building heating and cooling needs, together with appropriate zoning and transportation planning both of which could decrease urban heat island effects. But, when considering current housing scarcity, energy demand and prices, it is unclear what mix of measures is cost-effective (*e.g.*, to promote a wide use of air conditioning, to change building insulation standards and/or to create small urban parks that could mitigate the urban heat island). .

Also, as demonstrated in Hallegatte (2006) and Hallegatte *et al.* (2007a), uncertainty about the future climate is a strong obstacle to the implementation of early adaptation measures. Indeed, while the cost of adaptation is immediate, the benefits from adaptation measures are uncertain and delayed in the future. For instance, rejecting building permits in a zone that may become excessively vulnerable to hurricane storm surge, if hurricane intensity increases in the future, has an immediate political and economic cost. But the benefits of such a measure, namely limiting future losses are uncertain. These benefits depend on how hurricane characteristics will change in the future, which is still largely unknown. It is understandable, therefore, that costly adaptation and risk-management decisions are not always made, in spite of estimates suggesting that there will be long term benefits if climate change projections are correct. To avoid this problem, innovative strategies able to cope with these uncertainties (*e.g.*, “robust” decision-making, no-regret strategies, precautionary principle) have been proposed (Schwartz, 1996; Spittlehouse and Stewart, 2003; Lempert *et al.*, 2006; Lempert and Collins, 2007; Hallegatte, 2008b), but their application to adaptation policies is still in a very preliminary phase.

Finally, observation of current investments in risk reduction shows that current strategies are far from being optimal today (*e.g.*, Nicholls *et al.*, 2008), making it very unlikely that climate change adaptation will be optimal tomorrow. When considering possible adaptation strategies, one has thus to look at the details of how they can be implemented. In particular, especially but not only in developing countries, technical and financial obstacles can make it impossible for a given city or region to implement adaptation actions, even when benefits largely exceed costs. As a consequence, several adaptation scenarios should be assessed in impact assessments, to make a difference between (i) optimal adaptation measures that can be theoretically implemented if future climate and risks were known, and if decision-making processes were perfectly rational, and (ii) realistic adaptation strategies, that take into account political and economic constraints and uncertainties about future climate. Here, as mentioned above, it is suggested to carry out impact assessments considering three different adaptation scenarios to assess the scale and incidence of climate impacts and their policy implications, namely no adaptation, perfect adaptation and imperfect adaptation.

### *5.2.3 Co-effects of adaptation*

To fully measure the benefits from adaptation measures, it is essential to take into account also their positive and negative co-effects. For instance, massive air conditioning has been shown to increase the Urban Heat Island (and the associated outdoor discomfort) up to 1 °C (Kikegawa *et al.,* 2006). In this case, therefore, an adaptation option to improve comfort in buildings leads to added heat outside buildings and in buildings without air-conditioning.

In another example of negative side-effects, coastal infrastructure designed to protect the city against storm surge, such as sea walls, may threaten the tourism industry because they deteriorate landscape, ecosystem health and beach leisure attractions (Lothian, 2006). Beach landscape degradation, marine ecosystem damage and loss of leisure activity (*e.g*. diving) would surely lead to a drastic reduction in tourism flows – or at least to a decrease in the willingness to pay of tourists – leading in turn to declining local incomes. As a consequence, in some contexts, hard protection would simply not be an option. Also, even if successful cases do exist, geographers around the world have repeatedly demonstrated that adverse effects of dike construction are almost the norm in the past decades (see *e.g*. Paskoff, 1994). For example, hard protection has been shown to contribute to fish stocks depletion by further damaging coastal ecosystems (Clark, 1996). Since 90 percent of fish species depend on coastal zones at one point in their life cycle, (Scialabba, 1998), such coastal defences could have significant impact on fisheries economic activity.

Nevertheless negative side-effects may be offset to some extent by positive co-benefits of adaptation measures. Improving building insulation standards and climate-proofing new buildings is an example of a no-regrets strategy, since this action increases climate robustness while energy savings often pay back the additional cost in only a few years[15]. Land-use policies that aim to limit urbanisation and development in certain flood-prone areas (*e.g*., coastal zones in Louisiana or Florida) would reduce disaster losses in the present climate, and climate change may only make them more desirable. Also, in many locations, especially coastal cities, building sea walls would be economically justified to protect infrastructure and people from storm surge and flood risks, even with the current sea level (see Nicholls *et al.*, 2007), and sea level rise will only make these walls more socially beneficial.

In developing countries, vulnerability to current climate variability and weather events is estimated to be large in part because protective infrastructure is not in place to mitigate the impacts of such extremes. For instance, there is often insufficient drainage infrastructure to cope with heavy precipitation in urban areas. In this situation, development is likely to be the most efficient adaptation strategy as most adaptation strategies will include the development of infrastructures and institutions that are beneficial anyway because they help cope with climate variability. Water reservoirs are useful to cope with rainfall variability in the current climate, and they will also be very useful to cope with climate change. Development is an efficient adaptation strategy, however, only if development policies take into account future changes in climate conditions. In particular, it is critical to take into account expectations about climate change in the design of this new infrastructure otherwise it is at risk of being mal-adapted (and possibly useless or dangerous) over the medium to long term.

In the health sector in developing countries, it is often difficult to distinguish between adaptation measures and development measures: For instance, improvements in the health care system to answer climate change impact would be clearly beneficial, even in the absence of climate change, and it would be a very efficient adaptation strategy.

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[15] It has to be mentioned, however, that building design options that save heating energy may have detrimental consequences on summer comfort and air-conditioning energy consumption (*e.g*., large windows). As a consequence, optimal design depends to a large extent to climate conditions.

In the least developed countries, moreover, adaptation strategies may have to focus on capacity building and institutional capacity before considering "harder" investments (OECD 2009b). Institutional capacity, for example, is a requirement to implement adaptation options based on land-use planning.[16] Again, capacity building is likely to yield non-climate benefits and can accelerate decision-making in other areas.

Finally, it is important to take into account trade-offs and synergies between adaptation action and local mitigation policies, which are particularly important at the city scale. For instance, decreasing building heating and cooling needs or improving transportation planning are useful adaptation measures, as they decrease urban heat island effect and energy demand, but can also been seen as mitigation strategies, as they help reducing GHG emissions. On the other hand, using air conditioning to reduce city heat wave vulnerability and increase in-door comfort would increase energy consumption and possibly counter local or national mitigation efforts. Also, increasing the number of parks to limit the urban heat island would reduce urban density, possibly leading to increased transportation demand and energy consumption. Since adaptation and local mitigation use the same policy levers (*e.g.*, urban planning, transportation infrastructure, building standards), they have to be designed in a consistent framework. So, while global mitigation objectives are defined independently of adaptation policies (see Section 2), at local scales it is useful to design adaptation and mitigation policies together.

### *5.3 From sectoral losses to systemic losses*

Different economic actors are interested in different types of information about climate change. For instance, city planners and flood protection designers want to know how hurricane landfall probabilities will change, while insurers focus mainly on average annual direct losses and probabilities of exceeding a given level of damages. But governments and city authorities cannot consider only sectoral losses when designing adaptation policies and actions. The communities they represent, indeed, suffer not only from sectoral loss but also from the systemic losses. In cities, these systemic losses include (i) indirect consequences of the sectoral losses occurring in the city (that can be positive or negative); (ii) propagation from climate change impacts occurring outside the city.

Indirect consequences of sectoral losses in the city can be significant. Sectoral losses, indeed, can be smoothened or amplified (i) by spatial or sectoral ripple effects of the direct economic losses into the rest of the economic system over the short-term (*e.g.*, through disruptions of lifeline services after a disaster) and over the longer term (*e.g.*, through sectoral inflation and energy costs if energy production is affected, or through insurance prices and housing prices if risks increase); (ii) by responses to the macroeconomic shock (*e.g.*, by loss of confidence or change in expectations of economic actors, or by indirect consequences of inequality deepening); (iii) by financial constraints (*e.g.*, low-income households cannot easily adapt to climate change); and (iv) by technical constraints (*e.g.*, by the limited availability of skilled workers and of the most recent technologies in key sectors, by uncertainty in future local climate change).

Ripple effects from outside the city may also be very important, as can be illustrated by three examples. First, cities are not isolated economic systems: they import many goods and services (*e.g.*, many kinds of commodity) and they also export many things (*e.g.*, financial services). Decreases in productivity or income outside the city may therefore lead to a decrease in demand and an increase in import prices that could in turn affect the profitability of many economic sectors in the city and the income of city inhabitants. Second, climate change impacts outside the city can include strong decreases in agricultural productivity. In addition to the previous ripple effects, a decrease in agricultural production can lead to

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[16] This does not mean that capacity building is always present in developed countries. Assessing risk management policies in developed countries often highlights insufficient institutional and legal framework.

food security issues in absence of perfectly functioning world food markets. Security issues can then perturb all economic activities. Third, a decrease in farmer income would lead many of them to migrate to the city, in search for alternative jobs. The adverse consequences of rapid and uncontrolled increase in urban population are well known. In particular, they include the impossibility for basic infrastructures (and especially water management infrastructure) to cope with the larger number of inhabitants, leading to health issues and increased vulnerability to natural disasters.

All these indirect impacts are very difficult to assess. In spite of these difficulties, however, taking them into account is essential to assess in an unbiased way possible adaptation options. The next section summarises a few attempts to do so.

#### *5.3.1 Assessing systemic losses at the city level*

The assessment of systemic losses leads to spatial-scale issue. What is, indeed, the pertinent spatial scale to assess economic losses? It is the national scale or the regional scale, or does an analysis at the city scale make sense? From existing literature, it seems that assessments at the city- or region-scale have been considered pertinent when considering brutal shocks to the economy, namely natural disasters. On the opposite, longer-term and more progressive impacts have only been investigated at the national or super-national scales.

##### *Extreme events*

The assessment of the regional total cost of disasters is the topic of intense research (*e.g.*, Rose *et al.*, 1997; Brookshire *et al.*, 1997; Gordon *et al.*, 1998; Cochrane, 2004; Okuyama, 2004; Rose and Liao, 2005; Greenberg *et al.*, 2007). In this literature, however, no one pretends to reproduce all the mechanisms involved in disaster aftermaths. But the authors try to include as many indirect effects as possible. To do so, many models are based on Input-Output (IO) models, which are powerful tools to assess how a shock, on one or several sectors, propagates into the economy over the short- to medium-term, through intermediate consumption and demand.

Many papers using such models have investigated disaster impacts at the local or regional scales. Often, they also focus on the role of infrastructures: for water infrastructures (Rose and Liao, 2005), electricity distribution (Rose *et al.*, 1997), or transportation infrastructures (Gordon *et al.*, 1998; Cho *et al.*, 2001). They all conclude that indirect impacts are responsible for a significant share of total disaster losses, which is supported by empirical analyses of disaster consequences after, *e.g.*, the Northridge earthquake (Tierney, 1997; Gordon *et al.*, 1998; Boarnet, 1998), the Loma Prieta earthquake (Kroll *et al.*, 1991; Webb *et al.*, 2002); the hurricane Andrew (West and Lenze, 1994; Webb *et al.*, 2002); the Los Angeles black-out in 2001 (Rose and Liao, 2005); the 1993 Midwest Floods (Tierney, 1995).

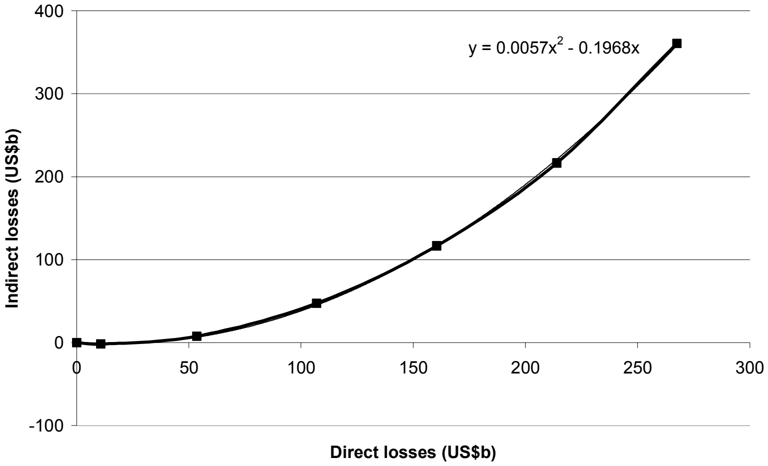
For instance, Tierney (1997) studies the impacts of the Northridge earthquake in 1994, and provides a very useful quantitative assessment of direct and indirect impacts. According to her analysis, the earthquake produced extensive lifeline service interruption and the loss of lifelines was a larger source of business interruption than direct physical damages. Moreover, nearly one business in four had problems with the delivery of goods and services following the earthquake and, on average, businesses were closed for about 2 days. In this case, direct damages to the business building were only the seventh cause of closure, present in 32% of the cases only.

Kroll *et al.* (1991) and Webb *et al.* (2002) investigate the consequences of the Loma Prieta earthquake (1989) on small business and on their ability to recover after the disaster. According to their analysis, the long term recovery of a small business depends on its location, the amount of direct losses it suffered, its level of inventories, and on local characteristics of the economy. For example, the economic consequences of the Loma Prieta earthquake have been limited in Santa Cruz, because this location was located farther from the earthquake epicentre, but also because (i) this economy was particularly diversified; (ii) the transportation network was very redundant; and (iii) the closure duration of utilities was short. They also find that small businesses suffered more from the disaster than larger ones, mainly because they depend more strongly on the local economy and because they cannot turn as easily to other customers after the disaster.

The indirect impacts of a disaster on a production network are found to depend on which sectors suffer the most from direct damages. For instance, the electricity sector plays an essential role for the whole economy, and its vulnerability to disaster can be crucial. In Rose and Liao (2005), for instance, the authors mention results by the National Federation of Independent Business concerning the impacts of the Los Angeles black-out in 2001. They found that one half of affected firms were forced to decrease their operations. Approximately 15.2% of firms suffered from indirect effects (because of disruptions in services and transportation), and 13.7% could not sell their production because the customers were not able to come. Importantly, they evaluate that the cost of the blackout was twice the cost of direct effects. These findings suggest that indirect impacts are often significant and highlight the need to focus on the mechanisms that lead to such impacts.

Applied to the Katrina landfall, Hallegatte (2008a) relates various amounts of sectoral losses to the corresponding systemic losses, calculated thanks to a regional Input-Output model. Figure 3 shows that, for the same sectoral structure as Katrina, systemic losses are increasing nonlinearly with total aggregated direct losses. When direct losses are below U.S. $40b, indirect losses are negative, thanks to the positive effects in the reconstruction sector, and systemic losses are lower than sectoral losses. It means that, for most disasters, the response of the economic system damps the shock and limits the economic consequences. But when direct losses exceed U.S. $40b, the economic system is not able to react efficiently any more. Indeed, a larger disaster causes more damages and reduces production capacity in the sectors involved in reconstruction. Because of the interplay of these mechanisms, the Economic Amplification Ratio (EAR), the ratio of systemic losses to sectoral losses, increases with the size of the disaster. For a disaster like Katrina, with about $100 billion sectoral losses, the EAR is found equal to 1.44. For a disaster with $200 billion sectoral losses, this ratio reaches 2.00, with systemic losses twice as large as sectoral costs.

**Figure 3. Indirect losses as a function of sectoral losses, for a disaster with the same sectoral structure than Katrina**



Note : The equation in black is the polynomial regression of indirect losses to sectoral losses, for this case study.

This relationship between systemic losses and sectoral losses has been estimated for the state of Louisiana in 2005, and for the consequences of Katrina. Of course, such study would probably give heterogeneous results for various states or countries, for instance because the production capacity of the construction sector differ. Results would also be different for different disasters, for instance because affected sectors would not be the same. Moreover, considering an economy in 2030 or 2080, as needed to assess climate change impacts, would lead to different results. Using the present IO table, possibly scaled to account for economic growth assuming that all sectors will growth at the same rate, corresponds to the suppression of the right-hand arrow in Fig. 1, from the top box on scenarios to the bottom box on systemic impacts.

Another example is the Western European heat wave of August 2003. It is estimated that 15,000 people died in France from its direct effects. It also had huge social, economic and environmental direct impacts, such as the destruction of large areas of forests by fire, and effects on water ecosystems and glaciers. As a results, the indirect effect of this event were large and included an increase in medical expenditure, a decline in productivity, propagation of the economic impacts through power cuts, transport restrictions, a decrease in agricultural production, and an increase in the price of many goods (see a complete analysis in Létard *et al.*, 2004). For instance, the wheat production decreased in 2003 by between 10 and 20%, with wheat prices 20% higher than during the summer 2002. This change, in turn, impacted the entire food industry. Also, the proportion of trains arriving on time decreased from 85% and 87% in 2001 and 2002 to 77% in 2003, leading to 15 million euros of additional client compensation for the national train company. These delays are likely to have had indirect consequences that are difficult to measure or predict. Finally, high temperatures lead to a decrease in shopping activity with, for instance, a 9% decrease in clothing sales in August 2003. Generally, outdoor shops in cities have seen fewer clients, while air-conditioned shopping centers have gained from the heat wave. The total losses, including direct and indirect impacts, are estimated to have exceeded 13 billion euros (UNEP, 2004).

Disasters may also have important longer-term economic consequences. Yet many of the published estimates assume that the city or region affected by a disaster will eventually fully recover and return to its pre-disaster situation. This assumption is not always the case, as illustrated by the city of New Orleans, which to date has not fully recovered from the landfall of Hurricane Betsy in 1965 and may not recover from the Katrina landfall. These long term consequences arise from changes in risk perceptions that deter new investments; and from clustered and increasing-return effects that lead businesses to move outside the affected area when many other businesses (especially basic services like utilities, schools, and hospitals) are strongly affected (Hallegatte and Dumas, 2008). Furthermore, a series of disasters could have especially large, negative consequences if reconstruction cannot keep pace with damage. This effect could arise from an amplifying feedback loop, for example in least developed countries, where there is a particularly low reconstruction capacity. In such contexts, the economic effects of a disaster occur over longer periods of time, making it more difficult to accumulate new capital to reconstruct and re-develop; the result is that such cities may remain at a lower development level than theoretically possible for an indefinite period of time (see Benson and Clay, 2004; Hallegatte *et al.*, 2007a).

Non-disaster-related indirect impacts of climate change could be important but have not yet been evaluated at the local scale, because of the obvious difficulties in doing so. However, some examples of national scale assessment exist. They take as input assessments of various direct climate-change impacts (*e.g.*, from increased temperatures on energy demand and health-care expenditures) and they investigate macroeconomic feedbacks (*e.g.*, how a reduced productivity would affect investment capacity and long-term prospects) and economic linkages between economic sectors (*e.g.*, how an increase in energy price would affect other sectors) at the national or international scale.

*Other indirect impacts at the national scale*

To evaluate long-term indirect impacts, one needs to use a long term dynamic model of the economy. In particular, input-output (IO) models that assume fixed technologies are no longer adequate in this situation. As a consequence, numerous studies use inter-temporal or recursive computable general equilibrium (CGE) models that incorporate economic and climatic modules in an integrated assessment approach at a national or global scale. While such studies exist at the national scale, they have not yet been undertaken at the city scale.

One example of a global CGE model that can assess national impacts is the WIAGEM model (Kemfert, 2002), which comprises 25 world regions, each with 14 sectors. This disaggregation permits to account for indirect effects of climate change such as sectoral and trade effects. The economic module is based on a classic general equilibrium approach and the model incorporates a climatic module and an energy module. This modelling framework allows an evaluation of systemic losses, on GDP or growth, thanks to economic relations and interlinkages between sectors and regions, in the 25 world regions. In Kemfert (2005), the author finds that total impacts are significant within the next 50 years: The impacts of climate change would reach almost 1.8% of the world GDP in 2050 if no action is taken, whereas with a strong climate policy, it would be less than 1% of the world global GDP. She finds that total impacts will be especially high in developing regions, reaching up to 3.5% of GDP in 2050 in China.

Similarly, Bigano *et al.* (2006) include in a CGE model a few sectoral impacts of climate change, such as sea level rise or decline in tourism due to warmer climate. To account for changes in tourism, they compute shocks as variations in the domestic expenditure on recreational activities, hotels and restaurant, generated by more or less tourists. Sea level rise is assumed only to affect the land available for agricultural production. They find that, for both tourism demand change and sea level rise taken separately, final effects on GDP are quite limited, negative in the case of sea level rise, slightly positive in some countries in the case of tourism. Developing countries are the more penalised but the joint impact of climate change induced increase or decline in tourism demand and sea level rise remains very low everywhere, less than 0.2% of the baseline GDP in 2050. The difference between these findings and those cited above (Kemfert, 2005) arises from varying assumptions on sector-level direct impacts, but also from the fact that they use very different assumptions on investment drivers. Kemfert assumes that climate change impacts and investments in adaptation have a crowding-out effect on other investments, leading to reduced economic growth, whereas Bigano *et al.* assume that these impacts and investments are taken out of consumption only. The fact that those results are so different shows how sensitive macro-economic results are to modelling assumptions on which little is known so far.

The CGE approach has also been applied to health impacts. Once a quantitative relationship between climate and health is determined, indeed, one can assess quantifiable economic impacts due to labor productivity decrease and changes in health care demand. For example, Bosello *et al.* (2006), estimate the economic impact in 2050 of climate-change-induced increase in diseases such as cardiovascular and respiratory disorders, diarrhoea, malaria, dengue fever and chistosomiasis. They interpret changes in morbidity and mortality as changes in labour productivity and demand for health care, and use it to shock a computable general equilibrium model. Unsurprisingly, they find that GDP and investment fall (rise) in regions with net negative (positive) health impacts.. However, these impacts remain small: in 2050, climate-change-induced health impacts may increase GDP by 0.08% (Rest of Annex I) or reduce it by 0.07% (in the rest of the world, which includes Africa).

While these models allow the assessment of long term climate change systemic impacts, their main drawback is that they are far too aggregate to assess city specific systemic impacts. A downscaling of their results would therefore be necessary to understand how national-scale impacts could translate into city-scale impacts. No such downscaling has been done so far.

### *5.3.2 Adaptation to reduce indirect losses*

Adaptation options able to reduce direct losses were discussed in Section 5.2.2. But different adaptation options may be able to reduce systemic losses, independently of sectoral losses. As explained in Section 5.3.1, indirect losses arise mainly from propagation through economic sectors and from production losses during the reconstruction in the case of natural disasters. Measures can be implemented to limit these two sources of indirect losses.

*Extreme events*

First, a resilient economic, *i.e.* an economy able to cope with a disaster in an efficient manner, is an economy where all producers are not too dependent on their suppliers. This can be the case (1) if the production of the most important production factors (especially the non-stockable goods like electricity) can be rapidly restored; (2) if each company has several redundant suppliers, implying that if one of its suppliers becomes unable to produce, the company will not be forced to stop its own production; (3) if companies have inventories and can keep producing even when a supplier cannot produce. In that respect, the most recent and efficient industrial organisation, with a limited number of suppliers, on-demand production, and small stocks, increases the vulnerability of the economy to disasters.

The resilience is also increased if imports from outside the affected region can replace local production. To do so, essential infrastructures have to be repaired as fast as possible, to reconnect the affected region to the rest of the economy: roads, railways, ports, airports, phone, internet, etc. Much can be done to improve this aspect of resilience: (i) making sure that utility companies and the organisations in charge of transport and communication infrastructures can mobilise enough workers to restore rapidly their services; (ii) facilitating imports in case of disasters (*e.g.*, by simplifying administrative requirements). The efficiency of emergency services and management plans can lower the indirect impacts and new institutional structures can be created (see for instance, Hecker *et al.*, 2000), to facilitate a more rapid recovery after the event.

Second, the pace of reconstruction is also important to restore production and housing. Utility companies and the institutions in charge of transport infrastructure must be equipped to face large-scale disasters and reduce as much as possible the period during which their production is interrupted or unreliable. In addition, the construction sector has a specific role in a disaster aftermath. There are numerous examples of cases where the reconstruction was slowed down by the lack of qualified workers in the construction sector. For instance, after the explosion of the AZF chemical plant in Toulouse, France, in 2001, tens of thousands of windows had been damaged, and the number of glaziers was far insufficient to satisfy the demand, even though glaziers from all over France came to Toulouse. In the same way, after the particularly destructive hurricane season in 2004 in Florida, roofers were unable to satisfy the demand and reconstruction costs increased by up to 40 percent in some regions (Hallegatte *et al.*, 2008b). In most cases, reconstruction involves a few specialties (among which glaziers and roofers), and increasing the number of such specialists can reduce in a significant manner the reconstruction duration. As a consequence, preparing for disasters by organising a special status for foreign workers in needed specialties can speed up the reconstruction, and therefore reduces the total cost of a disaster. Also, administrations can facilitate reconstruction, for instance by making it easier and faster to obtain building permits.

Finally, disasters can also create opportunities for upgrading infrastructure that would otherwise be outdated. For instance, when a factory has been destroyed, the reconstruction can be done using the most efficient new technology, therefore improving productivity. Examples of such improvement are: (a) for households, the reconstruction of houses with better insulation technologies and better heating systems, allowing for energy conservation and savings; (b) for companies, the replacement of old production technologies by new ones, like the replacement of paper-based management files by computer-based systems; (c) for government and public agencies, the adaptation of public infrastructure to new needs, like the reconstruction of larger or smaller schools when demographic evolutions justify it. Capital losses could, therefore, be limited by a higher productivity of the economy in the event aftermath (see also Albala-Bertrand, 1993; Stewart and Fitzgerald, 2001; Okuyama, 2003). Several factors, however, make it doubtful that this effect dominates in the aftermath of a disaster (Benson and Clay, 2004; Hallegatte and Dumas, 2008a). This is because production has to be restored as fast as possible to avoid high or disastrous losses, especially for small businesses. In addition, productive capital is usually only partially destroyed, and the remaining capital creates “inheritance” constraints on replacement capital, preventing the uptake of new technologies limiting the ability of capital to go to “new” needs.

Non-climate co-benefits or co-costs also need to be considered when assessing benefits from these adaptation measures. Sometimes, the non-climate-related benefits are sufficiently large to justify the implementation of the measure. In such cases, the measure is said to be a “no-regrets” strategy. For instance, targeting efficient and redundant energy supply networks to avoid blackouts during extreme heat entails an increased robustness of the energy supply system during any event, such as a terrorist attack or a purely technical incident.

*Other impacts*

Some regions and sectors will be particularly affected by climate change, like for instance those regions that depend on agriculture and fisheries, or on tourism (especially mountain regions). These losses of activities can lead to significant indirect economic losses and unemployment. The situation in these regions will require action on the qualification and redeployment of workers (ETUC, 2007). However, past experience of deindustrialisation (*e.g.*, in industrial regions of the U.S. or in coal-producing region in Europe) have shown how difficult it is for a region to shift from one activity to another. When the main activity of a region disappear, inhabitant revenue and local authority revenues (through taxes) decrease, making it more difficult to invest in new business and less attractive for alternative businesses to settle down. In most cases, these regions have needed help from national government (*e.g.*, through tax-free zones) to create new activities to compensate for the lost ones. If climate change forces many regions to change their business model, transitions may reveal difficult to manage (see Berger, 2003), and specific adaptation policy may be useful to make the transition more rapid and less painful.

## 6. Benefits and costs of mitigation strategies

As explained in the methodological roadmap, we suggest that mitigation benefits can be assessed across three distinct adaptation scenarios representing a continuum of different possibilities: no adaptation, imperfect adaptation (inspired by observations of the current situation), perfect adaptation. The no-adaptation and perfect-adaptation cases bracket possible outcomes; the scenario inspired from the current observation provides an idea of climate change costs if the world capacity to manage risks does not change significantly in the future.

Of course, the assessment of mitigation benefits has to be carried out with assumptions on the global climate response to a given emission scenario. For instance, an assessment of mitigation benefits from avoided impact of sea level rise depends on whether the IPCC or the Rahmstorf estimates of future sea level rise are used. Also, different models project very different response of the carbon cycle to anthropogenic emissions, making climate more or less sensitive to human activity. As proposed above, it is preferable to assess mitigation benefits using both an optimistic and pessimistic assumptions about climate change, in order to bracket the uncertainty and provide more than best-guess estimates.

This methodology provides an approach to assess direct local benefits from global mitigation through the estimation of avoided economic impacts of climate change as a function of assumptions concerning climate response, direct impacts, and adaptation efficiency. But mitigation strategies also have indirect effects in other non-climate change areas (see Table 2). To comprehensively estimate the benefits of mitigation policy it is necessary to also assess co-benefits (or co-costs) of action. In the case of cities, the main co-effects of GHG mitigation in cities are likely to derive from shifts away from fossil fuel use, for example in the transport or industrial sector, leading to lower levels of urban air pollution and net health benefits in urban areas.

Current estimates of co-benefits suggest that human health benefits may be large and significantly offset the (local) costs of mitigation (OECD 2001; Davis *et al.,* 2000; IPCC 2007b). More recent analysis, commissioned by the OECD to complement formal macro-economic analysis of the costs of mitigation, indicates that co-benefits of mitigation may be highest in OECD countries rather than outside of the OECD. Many of these national estimates of co-benefits derive from changes at the urban scale, *i.e.* population exposure to air pollution use (Cifuentes, 1999, Davis *et al.,* 2000; Kunzli *et al.*, 2000)

The choice of technology or specific end-point of mitigation measures will determine the size and nature of local co-benefits. Urban co-benefits of mitigation are likely to be particularly significant for measures in the transport sector where measures may lower the use of petrol or diesel in private or freight vehicles, in turn leading to significant decreases in local particulate emissions and large gains for human health. Also important are measures that reduce traffic levels through modal shifts away from private vehicle use towards public transport systems, thus leading to greater safety, lower congestion and noise levels, and ultimately more economically productive cities with improved quality of life. On the other hand, the use of more fuel-efficient diesel engines instead of petrol engines would likely lead to co-costs as this would lead to an increase of black carbon emissions (Kupianen and Klimont, 2004) and losses in terms of human health.

Tropospheric ozone formation is another major urban health risk which is accelerated by aerosol emissions from fossil fuel combustion and natural sources as well as by atmospheric methane which is a potent GHG stemming from a variety of different agricultural and waste sources. While methane emission sources may be located outside of urban areas, mitigation measures affecting methane in nearby regions would also be likely to lead to important health co-benefits in urban areas (Reilly *et al.*, 2007).

The assessment of co-benefits starts from a baseline scenario, this time for air pollution without additional climate change mitigation strategies and with a given set of expectations about future air pollution policy in the location in question (Morgenstern, 2000). For example the economic impacts of air pollution under a given mitigation strategy can be evaluated with statistical methods linking health and air pollutants, to health impacts through epidemiological studies (*e.g*. Thurston et al, 1997; Davis *et al.*, 2000; Kunzli *et al.*, 2000). Here again, the value of health must be assessed, considering both quantifiable economic effects, such as the fall in productivity, medical expenditure, value of time loss from school, *e.g*. Weiss et al, 2000) and intrinsic value of health.

**Table 2.Cities related aims and co-benefits of sector policies to reduce GHGs**

| Sector | Climate policy aims and benefits | Other (non-climate change) benefits |
|---|---|---|
| Electricity production and industrial energy use | Encourage fuel switching from coal and oil to low or no-emission energy sources, such as combined heat & power, renewable energy and energy efficiency, to reduce $CO_2$ emissions | Raises urban air quality and limits regional $SO_x$ and $NO_x$ air pollution, preserve water quality, increase energy security, all of which can deliver local benefits |
| Residential & commercial energy: buildings, office equipment & appliances | Lower energy use requirements of housing and household services, reduce $CO_2$ emissions | Lower investment costs for energy suppliers and possibly smooth load; lower operating costs for commercial entities & consumers and avoids regional air pollution from (unnecessary) electricity and/or heat generation; improve comfort and affordability; raise energy security |
| Transport | Raise the efficiency and emission performance of vehicles and manage demand, reduce $CO_2$ and possibly other GHG emissions | Lower congestion in cities and limit harm to human health from urban air pollution; lower dependency on oil imports to raise energy security.<br>However co-costs may also exist *e.g.* increased diesel fuel use lowers $CO_2$ but increases particulates, which have human health risks; also catalytic converters lower $NO_x$ emissions but raise $N_2O$ and $CO_2$ emissions |
| Waste | Minimise waste, increase recycling and material efficiency in production and packaging, reduce $CH_4$ emissions | Limit needs for costly and unsightly landfilling; improve economic performance |

Even when mitigation measures change the mix of fuels or technologies for power generation or industrial activities that are likely to be located outside of urban areas, there may also be urban co-benefits in nearby or downwind cities due to lower regional emissions of $SO_2$ and $NO_x$ (acid pollutants) and avoided damages to built infrastructure. For example, the relationship between energy saving and material damages to buildings, through $SO_2$ emission reduction was investigated by Aunan et al, 1998, in the case of Hungary. Using historical statistical relationships, they find that the implementation of energy saving programs can lead to significant benefits (30–35 million US$ annually in Budapest only). Thus regional or national mitigation strategies can have urban co-benefits and these should be accounted for in any assessment of the city-scale benefits of climate policies.

Moreover, local strategies will affect urban inequality – also known as distributional impacts. For example, Gusdorf *et al.* (2008) find that the rapid implementation of a transportation tax could have major redistributive effects throughout urban areas: consumers living far from the centre have a stronger burden than other inhabitants to cope with, and they cannot immediately move to more favourable locations, because housing is not yet available close to employment centres. The magnitude of the redistributive effects is found to be directly and nonlinearly related to the magnitude and pace of the change in transportation cost. In another analysis, Bernstein *et al.* (2000) show that there are strong distributive benefits from California's aggressive energy efficiency policies; these include lower energy costs for poor households who spend a relatively higher share of their income on energy bills. Clearly, more research is needed on the distributional aspects of climate change impacts and policies.

Finally, climate change mitigation strategies may also lead to a diversification of energy sources, which in turn would decrease systemic losses due to a disruption of supply (not necessarily due to climate change). As mentioned above, such a strategy can also be part of an adaptation strategy to respond to the risk of climate change induced systemic losses. This is an example of where adaptation and mitigation strategies overlap, and suggests the need to consider them in an integrated framework especially at urban scale. Finally, as stated in Section 5.2.3, adaptation and mitigation policies in cities will sometimes use the same investment or policy levers: in transportation infrastructure, in the built environment through urban planning, architecture and other regulations, and in energy production and use. Adaptation and mitigation strategies at urban scale are therefore usefully designed within a single integrated framework that has sustainable urban development at its centre. This has important consequences in terms of public policy and decision-making process.

## 7. Conclusions

This paper presents a methodological roadmap to assess the economic impacts of climate change in cities. To go from the large-scales of climate change projected by global climate models to its consequences on a city and its inhabitants, one has to follow a long and complex series of steps. First, one has to select a global socio-economic and mitigation scenario and to derive from them global emission and climate scenarios. Then, it is necessary to downscale large-scale climate change at the spatial scale that is pertinent to investigate economic impacts at a city level. Then, one has to translate local climate changes into sectoral losses or gains. Of course, adaptation strategies can and will also be undertaken to limit these sectoral losses and these possibilities have to be investigated, including the barriers and limits to adaptation, and their possible co-benefits or adverse co-effects. Economic mechanisms will inevitably introduce a range of interactions within the broader economic system to reduce or amplify direct losses: diffusion of impacts from one sector to another in the city, macroeconomic feedbacks, diffusion of climate change impacts from inside to outside the urban-area. These indirect effects have to be investigated to assess the systemic impact of climate change in a city. Again, adaptation strategies can reduce indirect losses, for instance through diversification of the city economy to avoid an undesirable dependency to a vulnerable sector. Finally, this method allows bracketing a plausible range of outcomes relating to global mitigation action compared to a situation with no new action.

As uncertainty is introduced in each of the steps of a local impact assessment, the methods are designed to address uncertainty by bracketing results around a range of “plausible” parameters. The fact that precise “predictions” of future impacts is out of reach does not mean that such analysis cannot be used to inform policy decisions. Indeed, despite the uncertainty, economic impact estimates allow for a better understanding of the human activities affected by climate change and for an estimation of the (market) values at stake. They can be used to assess and recommend adaptation options and to assess the local benefits of global mitigation options. For example, city-scale assessments of the impacts of climate change can provide local populations with a better understanding of the benefits of aggressive mitigation strategies (and the risks of inaction), in part by “localising” that understanding. Because all climate policy strategies need time to mature and become effective (*e.g.*, changes in urban planning), analyses at the city scale have immediate value to bring attention to climate change amongst local decision-makers and to inform debate about the range of possible response options regarding both adaptation and mitigation.

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