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LITERATURE REVIEW ON CLIMATE CHANGE IMPACTS ON URBAN CITY CENTRES: INITIAL FINDINGS

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ABSTRACT

There is an increasing recognition of the impacts of climate change in cities. Around half of the world's population live in cities, and they act as centres of economic and political activity within countries and regions. There is therefore a growing resonance in considering city-scale issues in order to progress climate policy discussions. Against this background, the OECD has commissioned a study to undertake a literature review on climate change impacts on urban areas (cities), and to review and evaluate the methods used in the published literature, to formulate policy relevant conclusions on the basis of this literature, and to identify evidence gaps and research needs.

Climate change is most likely to have important impacts on cities in coastal or riverine locations, in resource-dependent regions, and in locations at risk at risk from extreme weather events, especially those undergoing rapid urbanisation or whose economies are closely linked with climate-sensitive resources (see the IPCC 3rd and 4th Assessment Reports). City-scale vulnerability is therefore a function of location, economy, and size. The present study undertakes a more in-depth review of the city-scale studies of impacts, and their treatment of adaptation.

There are a small, but growing, number of city studies. Detailed analyses of city-scale impacts across multiple sectors are largely limited to a handful of large metropolitan areas, most notably London, New York, and Boston. These include identification of potential impacts, some quantitative and economic analysis, and some consideration – though not detailed appraisal - of adaptation options. There are also quantitative impact studies in cities in Canada, Australia and New Zealand (e.g. Toronto, Montreal, Vancouver, Sydney, Melbourne, Wellington), and limited city-scale analysis as part of wider regional studies (e.g. Los Angeles in California). A much greater number of cities have undertaken partial analysis or detailed qualitative assessment, with examples in most major OECD and some non-OECD regions.

The literature review collates evidence by sector/theme, including sea level rise (and storm surge) on coastal cities, infrastructure damage from extremes, health, energy use, water demand and water availability, tourism and cultural heritage, urban biodiversity and air pollution. Most studies have focused on coastal cities and there is little information to date on inland cities. There is also a major evidence gap on the quantification of climate change impacts such as energy and water resources from changes in climate variable means.

A number of policy aspects are highlighted.

The limited evidence suggests that projected changes in climate will have wide-ranging impacts and economic effects on cities (compounded by other factors), though the overall net economic effects are uncertain. Impacts are likely to be more important for developing country cities.

City-scale initiatives are currently focused on awareness-raising rather than impact assessment and adaptation analysis, with the potential consequence that no-regret adaptation options which increase the resilience to climate change are being missed. Lessons from the more advanced studies suggest that this type of analysis can be incorporated into current planning and decision-making and show that the establishment of a designated lead organisation is an effective means of co-ordinating activities, and that engagement with key sectoral stakeholders is essential.

A number of research priorities are identified, including the need for further scoping studies, investigation of transferability of results, additional impact areas, progress in a range of methodological issues (impacts and adaptation), and the need for an institutional perspective on processes to effectively co-evolve city-scale adaptation and mitigation strategies.

FOREWORD

This report is part of an OECD project on Cities and Climate Change. A priority of this project is to explore the city-scale risks of climate change and the benefits of both (local) adaptation policies and, to the extent possible, (global) mitigation strategies. The current study is one of the first products to emerge from the project. A companion OECD report – on exposure and vulnerability of global port cities to coastal flooding -- is being issued in December 2007 and additional reports are planned in 2008, including in depth city case studies.

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TABLE OF CONTENTS

EXECUTIVE SUMMARY

Warming of the climate system is unequivocal (IPCC, 2007) and without significant changes, the trend in global emissions of greenhouse gases and climate change will continue. These changes will lead to wide ranging impacts and economic costs across different sectors and regions. At the same time, there is an increasing recognition of the potential impacts of climate change in cities. Around half of the world's population currently live in cities (UN, 2006), and the proportion is set to rise further in future years. Cities are also the centre of economic and political activity, and there is a growing resonance in considering city level issues as a means to progress climate policy discussions. Against this background, the OECD has commissioned this review with the following aims:

- To undertake a literature review on climate change impacts on urban areas (cities);
- To review and comment on the methods used, and provide an overview and summary of quantitative and monetary estimates of climate change impacts for different locations;
- To formulate policy relevant conclusions;
- To discuss the gaps in understanding and to identify research needs.

The IPCC Third Assessment Report (TAR) (2001) concluded that climate change is most likely to have important impacts on settlements in coastal or riverine locations and resource-dependent regions, and that vulnerability was a function of location, economy, and size. The IPCC 4th Assessment Report (2007b) extends this to cover those areas at risk from extreme weather events, especially where rapid urbanisation is occurring, and those areas whose economies are closely linked with climate-sensitive resources.

This study has undertaken a review of the literature on studies of climate change on cities. It has found an emerging literature on this subject, though the studies are mostly qualitative in nature. Nonetheless, a small number of studies have undertaken detailed analysis of city scale impacts across sectors, notably London, New York, and Boston. These include detailed estimates of potential impacts, some quantitative and economic analysis, and consideration of adaptation options. However, even for these cities, the analysis remains partial. There are also impact studies in cities in Canada (e.g. Toronto, Montreal, Vancouver) and Australia and New Zealand (e.g. Sydney, Melbourne, Wellington), as well as sea level rise studies in Alexandria and Singapore, and some city scale analysis as part of wider regional studies (e.g. Los Angeles in California). A much greater number of cities have undertaken some partial analysis or detailed qualitative assessment. This includes cities in most major OECD regions, and many non-OECD regions.

While there is a wide coverage of locations across continents, most studies have focused on coastal cities – there is very little information on inland cities and some key vulnerable coastal regions are still not covered. There is a major evidence gap on the impacts of climate change across the range of geographical locations and impact categories, e.g. energy demand, water resources and riverine flooding, the current literature is therefore only indicative of the issues and levels of impacts.

The literature review has also collated the key issues and the state of evidence by sector/theme for cities. These relate to sea level rise on coastal cities (and storm surge), infrastructure damage from extremes, health, energy use, water demand and water availability, tourism and cultural heritage, urban biodiversity and air pollution. This sectoral analysis shows a strong variation in impacts with location and site. However, two important conclusions can be made. First, it is not just coastal/riverine and climate dependent cities that will be affected by climate change. Second, in addition to extreme events, mean changes in climatic variables will lead to potentially significant city-scale impacts, particularly in relation to energy use.

The review has also considered methodological issues. Understanding and improving methodological approaches, and the way they can affect the impacts and economic cost estimates, is essential to ensure that this type of information can be effectively used in city analysis. Several areas are highlighted to improve methods and consistency between studies, and these include the use of climate modelling, socio-economic scenarios, the coverage of impacts and economic analysis and values.

A number of policy aspects are highlighted:

- The limited evidence available suggests that projected changes in climate (compounded by other factors) are expected to have wide ranging impacts and economic effects on countries and therefore cities in the OECD, and other world regions. The overall net economic effects are uncertain, not least due to the present limits on quantification and valuation, but are potentially very significant. Impacts are considered to be more important for developing country cities – reflecting identified regional vulnerabilities – a conclusion based primarily on the fact that the populations of these cities are in many cases growing faster than their physical infrastructure, and that their exposure to climate change is greater than in developed countries, the latter fact reflecting their overwhelmingly tropical locations and development levels.

- The lack of city-scale quantitative analysis suggests that institutional actors in urban centres are not yet considering specific adaptation action. Instead, the focus tends to be more on awareness-raising across the range of stakeholders. There is a danger, therefore, that no-, or low-regret options that increase resilience to climate change, or that support city-scale mitigation actions, will be missed. Lessons from the more advanced mega-cities, e.g. London and New York, suggest that climate change impacts can be incorporated into current planning and decision-making as long as there exist the institutional structure and capacity to co-ordinate initial scoping and development of impact assessments, including the development of local/regional climate change scenarios. However, one emerging theme is that even in the most developed examples, there is little robust appraisal of adaptation options, serving to emphasise that cost-effective and proportionate responses are not yet being identified.

- The mega-city case studies show that establishment of a designated lead organisation or unit within an organisation is an effective means of co-ordinating initial scoping activities, and that engagement with key sectoral stakeholders is essential if the benefits of these initial activities are to be maximised. There are also advantages in terms of consistency and economies of scale in adopting comparable procedures in the initial and subsequent impact and adaptation analysis. For example, it is useful for stakeholders to agree on the use of common climate scenarios as well as common assumptions regarding the projection of socio-economic scenarios, or at least to be aware of why differences exist.

Finally, a number of research priorities are identified.

First, the lack of coverage across a number of world regions and impact categories suggests that a number of scoping case studies should be undertaken – possibly on a pooled funding basis, in order to allow other cities to explore the transfer of results between cities with similar location or vulnerability characteristics. Subsequent studies could be then undertaken where there are specific vulnerabilities and where the initial studies identify impacts that justify quantitative analysis to inform current investment and development decisions and strategies.

Second, while sea level rise and extremes are obvious initial research areas, the lack of evidence cautions against a focus on these two categories alone. This is particularly important in moving from a generic assessment of the priority of physical impacts, to a quantified analysis of the monetary damages. The issue of energy demand (particularly in warmer cities), is shown here to be potentially very significant, especially in economic terms, and this should also be a priority. Additional impacts on health and water scarcity also warrant further investigation.

Finally, work is needed on methodological issues, especially given the wide variability in approach to socio-economic scenarios, impact assessment and valuation in the existing studies. Most studies reference the need to adapt. But while there are some detailed accounts of the options available to counter or adapt to specific impacts, much more work on evaluation of adaptation responses is needed, including the economics of adaptation.

1. Introduction

1.1 Background

The Fourth Assessment Report Working Group I (WG1) of the Intergovernmental Panel on Climate Change (IPCC, 2007a) has concluded that '*Warming of the climate system is unequivocal'*, and that *'discernible human influences now extend to other aspects of climate, including ocean warming, continental-average temperatures, temperature extremes and wind patterns'*. The Report also assesses the likely range of future climate. For example, by 2100, the best estimate of global surface temperature across the IPCC SRES scenarios is a rise of 1.8 to 4°C with a likely range of 1.1 – 6.4°C in relation to 1990 levels, and a global mean sea level rise of between 18 to 59 cm. The WGII report (IPCC, 2007b) documents that the impacts of climate change are already being observed: with 75 studies with some 20,000 observations documented of current effects on physical and biological systems.

The future impacts of climate change will lead to wide ranging impacts across different sectors and regions. The broad range of impacts of climate change (IPCC, 2007b) include effects on agriculture, fisheries, desertification, biodiversity, water resources, heat and cold related mortality, coastal zones and floods. These are increasingly linked with significant economic damages, and consideration of these costs is increasingly helping to inform the policy debate (e.g. as with the Stern Review, 2006).

The OECD itself has been active in this policy area, hosting two expert workshops. The first meetings culminated in an OECD book published in 2004 '*The Benefits of Climate Change Policies: Analytical and Framework Issues*' (Corfee-Morlot and Agrawala (Eds), 2004). The second (OECD Global Forum on Sustainable Development Workshop on the Economic Benefits of Climate Change Policies, Paris, 6 – 7 July 2006), brought together more than twenty experts to survey the current state of knowledge on the economic benefits of climate policies, and to think about what should be done next to advance understanding of those benefits in the face of uncertainty and acceleration in the pace of observed effects[1]. The OECD has supported studies of metrics for evaluating the economic benefits of climate change policies for sea level rise by Nicholls et al (2006) and agriculture by Rosenzweig and Tubiello (2007).

[1] The papers are available at www.oecd.org/env/cc/benefitsforum2006.

At the same time, there is an increasing recognition of the potential impacts of climate change in cities. Around half of the world's population currently live in cities – though the proportion is much higher in OECD countries, and globally the proportion is set to increase to 60% (some 5 billion people) by 2030 (UN, 2006)[2]. Cities are also the centre of economic and political activity, and there is a growing resonance in considering city level issues as a means to progress climate policy discussions.

The city scale is increasingly being recognised as a useful scale for mitigation actions (e.g. with the recent C40 Large Cities Climate Leadership Group[3]). Attention is now also considering the impacts of climate change itself on cities. Consideration of city impacts brings the issue of global climate change down to a local scale, which may be more relevant for many private and public agents who are charged with designing and implementing possible responses. It may also highlight the issues of impacts and variability for many (northern) OECD countries, which are not identified as hot spots in regionally aggregated analysis, and so encourage the political dimension of decision-making related to climate change. The IPCC also notes that many adaptive measures, (e.g. cooling buildings), associated with cities' built environment also have consequences for mitigation strategies. However, while a growing number of cities have begun bottom-up initiatives on greenhouse gas reductions, the role of cities and the interactions between city and national response policies is still largely unexplored in the search for effective and efficient responses to climate change. To address this, there has been a recent focus in OECD activities, including[4]:

- A special session on climate change and cities in the OECD international conference: "What Policies for Globalising Cities?" held in Madrid in March 2007, organised jointly with the Madrid City Council and the Club of Madrid (former Head of States).
- A roundtable discussion on "climate change and cities" in the meeting of the Working Party on Territorial Policy in Urban Areas held in June 2007 in Rome.

It is also evident that even under strong mitigation scenarios, changes in climate will continue for many decades. Therefore, it is essential that human systems, including cities, develop adaptation responses to avoid the risks posed by, and to take advantage of the opportunities arising from, unavoidable global climate change.

1.2 Objectives

Against this background, the OECD has commissioned this review with the following aims:

- To undertake a literature review on climate change impacts on urban areas (cities), including a description of impacts in qualitative and quantitative terms, and monetary units.
- To provide information on adaptation responses and the difference that these can make in reducing impacts.

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[2] Urban dwellers represented 49 % of the global population in 2005 compared to 29 per cent in 1950. By 2008, half of the world's population is projected to be urban; by 2030, nearly 5 billion urban residents are expected worldwide, representing 60 % of the population at that time. Note that In Europe the proportion of the population residing in urban areas is expected to rise from 72% in 2005 to 78 % in 2030 and in Northern America, from 81 % in 2005 to 87 % in 2030. The majority of urban dwellers live in small cities (i.e. less than 0.5 million inhabitants).

[3] http://www.c40cities.org/?utm_source=london.gov.uk&utm_medium=link&utm_content=text-link

[4] http://www.oecd.org/dataoecd/59/56/39211353.pdf

- To review and comment on the methods used (and methodological issues) to conduct such assessments, as well as an overview and summary of any quantitative estimates of climate change impacts for different locations.

- To formulate policy-relevant conclusions.

- To discuss the gaps in understanding of how climate change will affect cities, and to identify research needs.

The study is intended to facilitate information sharing among OECD member countries and learning from 'good practices' in assessments of economic costs of climate change for cities.

The report has a different focus to other recent reports and reviews (Stern, 2006; IPCC, 20007b). The Stern review takes a global perspective on the economics of climate change and focuses on the aggregate total costs and benefits (with benefits derived from integrated assessment models, and based on implicit methodological assumptions). The IPCC Working Group II (IPCC, 2007b) presents the current scientific understanding of impacts of climate change on natural, managed and human systems, the capacity of these systems to adapt and their vulnerability, including for settlements.

This report focuses specifically on cities, and explores the extent to which economic analysis has been incorporated into the climate change impacts at this scale. It also considers the specific issues with this city scale analysis, and the issues for progress within local institutional frameworks. The ultimate intention of the review is to identify whether the potential advantages of undertaking city-scale impact analyses are being exploited fully, particularly with regard to including economic considerations of impacts, and what are the limitations to such analysis.

1.3 Definitions

With the rapid growth of literature on climate change, concepts and definitions continue to be re-defined. This is an area where the OECD has been active, with the recent publication '*Adaptation to Climate Change: Key Terms'* (Levina and Tirpak, 2006), which found that various definitions of the key climate change impacts / adaptation terms and concepts varied across institutions and different groups of stakeholders. A summary of the report findings on key terms are presented in the box below. In this review we use the definitions given by the IPCC, except where indicated.

Box 1. **Definitions**

Climate) Impacts are defined by IPCC TAR (2001) as: The consequences of climate change on natural and human systems. Depending on the consideration of adaptation, one can distinguish between potential impacts and residual impacts. Potential Impacts--All impacts that may occur given a projected change in climate, without considering adaptation. Residual Impacts--The impacts of climate change that would occur after adaptation.

Sensitivity is defined by IPCC TAR as: The degree to which a system is affected, either adversely or beneficially, by climate related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea level rise).

Vulnerability is defined by IPCC TAR as: The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. Levina and Tirpak found very different interpretations for vulnerability: one interpretation views vulnerability as a residual of climate change impacts minus adaptation, whilst another views vulnerability as a general characteristic or state generated by multiple factors and processes, but exacerbated by climate change.

Resilience is defined by IPCC TAR as: The amount of change a system can undergo without changing state. Levina and Tirpak found different definitions, including a) the capacity of a system to tolerate disturbance without changing state, and b) the ability to recover from the effect.

Adaptation is defined by the IPCC TAR as: Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation. Levina and Tirpak found alternative definitions from UNFCCC, UKCIP, and UNDP.

Adaptive Capacity is defined by the IPCC TAR as: The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. Levina and Tirpak found alternative definitions as a) implying that adaptation leads to increased adaptive capacity, b) that increased adaptive capacity increases ones ability to adapt, or c) that adaptive capacity indicates the possible extent/limit of adaptation.

Maladaptation is defined by the TAR as: Any changes in natural or human systems that inadvertently increase vulnerability to climatic stimuli; an adaptation that does not succeed in reducing vulnerability but increases it instead.

Mainstreaming. Levina and Tirpak found that a definition of 'mainstreaming' does not yet exist, although the term is widely used and seems to be used interchangeably with 'integration'. Mainstreaming refers to the integration of adaptation objectives, strategies, policies, measures or operations such that they become part of the national and regional development policies, processes and budgets at all levels and stages (UNDP, 2005)

It is often difficult or impossible to distinguish between impacts of, and adaptation to, climate change. For instance land abandonment due to sea level rise - or increased health care expenditure due to higher incidence of heath-related diseases - could be labelled also as impacts of climate change. However, all these processes are reactions that agents put in place to respond to it. Moreover, without them the costs of climate change will be higher. Accordingly we have described them here as adaptation. There is also often overlap between autonomous and planned adaptation.

Additionally for this report, we have to define 'cities'. There are many definitions, mostly relating to population density and size i.e. they are clusters of population over a certain size. For this report, we are primarily interested in major world cities. The UN population statistics separate urban agglomerations with 750,000 inhabitants or more. In this series of studies we use a cut-off for major cities of around 1 million though many of the findings of this literature review apply equally to smaller cities[5].

Also there is a need to define economic costs. Levina and Tirpak (in common with most of the literature) separate:

- Market Impacts - Impacts that are linked to market transactions and directly affect gross domestic product (GDP, a country's national accounts)--for example, changes in the supply and price of agricultural goods.

- Non-Market Impacts - Impacts that affect ecosystems or human welfare, but that are not directly linked to market transactions--for example, an increased risk of premature death.

The economic costs of climate change are also expressed in a number of different ways (see EEA, 2007). The economic effects of climate change impacts are often referred to (in European policy discussion) as the 'costs of inaction'. 'Inaction' is defined as the counterfactual or reference from which the costs and benefits of different policy or actions can be evaluated. Strictly speaking the 'costs of inaction' can reflect many different possible future reference scenarios, but in practice, the term is usually taken to represent the future baseline without mitigation (and planned adaptation). From this baseline, it is possible to assess the benefits of climate change policy.

The economic costs of climate change are often expressed as the 'social costs' i.e. they are a measure of change to social welfare and so include non-market values as well as market impacts. There are different ways that these can be expressed, depending on assumptions about e.g. the given baseline, scenario, the level of adaptation (whether included or excluded), and whether these costs refer to total or average costs, or marginal costs. The total social costs of climate change impacts reflect the total costs of the baseline scenario, either in a given future year (e.g. 2100), or as a total net present value over, e.g. the next 100 years or longer. The marginal social costs of climate change are usually estimated as the net present value of climate change impacts over the next 100 years (or longer) of one additional tonne of carbon or other GHG emitted to the atmosphere today.

1.4 Outline of report

Section 2 provides an overview of the impacts of climate change on cities, as currently documented in e.g. IPCC reports, and introduces a number of methodological issues specific to impact and adaptation costing that are relevant to our subsequent literature review. Section 3 presents a review of the literature on climate impact assessments of individual cities, summarising their key findings and pointing to their potential use in adaptation decision-making and development strategies more generally. This section also considers the treatment of individual impact types over the range of city studies, placing these in the context of impact analyses undertaken at a larger geographical scale. Section 4 reflects on the methodological issues that the city-focussed literature raises, particularly with respect to monetary quantification of climate change impacts, and how their treatment in this context relates to their treatment in the wider impact literature. Finally, Section 5 presents the overall conclusions of the studies and identifies the principal research gaps.

[5] Note that for other purposes different definitions may obtain. For example, the OECD Metropolitan database uses the dual criteria of a population density of > 150 people per km2 and total population > 1.5 million to define a metropolitan area (OECD, 2006).

2. The impacts of climate change on cities: an overview

2.1 Empirical evidence

There are a variety of potential impacts of climate change on cities. A number of reviews have investigated these effects, including the IPCC Third Assessment Report (TAR), 2001; Bigio, 2003; McEvoy, 2007; Wilby, 2007, IPCC Fourth Assessment Report (AR4) 2007b; and Huq et al, 2007, and generally identify the most important effects of climate change on cities as:

- Effects of sea level rise on coastal cities (including the effects of storm surges);
- Infrastructure damage from extremes (wind storms and including storm surges, floods from heavy precipitation events, heat extremes, droughts);
- Effects on health (heat and cold related mortality, food and water borne disease, vector borne disease) arising from higher average temperatures and/or extreme events;
- Effects on energy use (heating and cooling, energy for water);
- Effects on water availability and resources;
- Effects on tourism, and cultural heritage;
- Effects on urban biodiversity;
- Ancillary effects on air pollution.

There are also a set of additional secondary effects that indirectly affect cities, e.g. in relation to agriculture, ecosystems, etc. though these are not the focus of this review. Some of the literature also highlights a set of wider issues related to the concentration of economic activity in cities. These include potential effects that climate change may have on the physical assets used within cities for economic production and/or services, on the costs of raw materials and inputs to economic production, on the subsequent costs to businesses, and thus on competitiveness (or comparative advantage) and wider economic performance and employment patterns in the sub-region and beyond.

The IPCC TAR (2001) provided a comprehensive review of the physical climate impacts on cities, using the evidence available at that time. It concluded that:

> "*Climate change is more likely to have important impacts on the development of settlements in <u>resource-dependent regions</u> or <u>coastal or riverine locations</u>. Most of the concerns were of possible negative impacts on development (e.g., on the comparative advantage of a settlement for economic growth compared with other locations), although impacts on some areas were considered likely to be positive.*"

The TAR also concluded that vulnerability for settlements was mainly due to three factors:

1. Location (with coastal and riverine areas at most risk);

2. Economy (with those areas that are dependent on weather-related sectors at most risk),

3. Size (larger settlements have a greater aggregate risk, but also have greater adaptive capacity (resources) to mitigate impact risks.

The information from the TAR was summarised in Table 7.1 of the Impacts Report (chapter 7). The relevant urban scale parts of the table are reproduced below, with the degree of importance highlighted in colour.

Table 1. **Impacts of climate change on human settlements by impact type and settlement type (impact mechanism)**

	Type of Settlement, Importance Rating, and Reference								
	Resource-Dependent (Effects on Resources)		**Coastal-Riverine - Steeplands (Effects on Buildings & Infrastructure)**		**Urban 1+ M (Effects on Populations)**		**Urban <1 M (Effects on Populations)**		
Impact	Urban, High Capacity	Urban, Low Capacity	Urban, High Capacity	Urban, Low Capacity	High Capacity	Low Capacity	High Capacity	Low Capacity	Confid.
Flooding, landslides	L–M[1]	M–H[2]	L–M[1]	M–H[2]	M[1]	M–H[2]	M[1]	M–H[2]	H
Tropical cyclone	L–M[3]	M–H[4]	L–M[3]	M–H[4]	L–M[3]	M[4]	L[3]	L–M[4]	M
Water quality	L–M	M	L–M[5]	M–H[6]	L–M	M–H	L–M	M–H	M
Sea-level Rise	L–M[7]	M–H[6]	M[8]	M–H[9]	L[8]	L–M[6]	L	L–M[6]	H (L for res. dep.)
Heat/cold waves	L–M	M–H	L–M[10]	L–M	L–M[10]	M–H[11]	L–M[10]	M–H[11]	M (H for urban)
Water shortage	L[12]	L–M	L	L–M	L	M	L–M[12]	M	M (L for urban)
Fires	L–M	L–M	L–M	L–M	L–M[15]	L–M[16]	L–M	M	VL (M for urban)
Hail, windstorm	L–M[17]	L–M[18]	L–M	L–M	L–M[17]	L–M[18]	L–M[17]	L–M[18]	L
Agriculture/ forestry/ fisheries	L–M[19]	L–M[20]	L	L	L	L–M	L–M	M	L
Air pollution	L–M[21]	L–M	—	—	L–M[10]	M–H[22]	L–M[10]	M–H[22]	M
Permafrost melting	L	L	L	L	—	—	L–M	L–M	H
Heat islands	L	L	L	L	M[24]	L–M[24]	L–M[25]	L–M[25]	M

Source: IPCC TAR (2001)[6] Table 7-1.

Table note 1. Typeface indicates source of rating: References where indicates direct evidence or study. Impacts generally are based on 2xCO_2 scenarios or studies describing the impact of current weather events (analogues) but have been placed in context of the IPCC transient scenarios for the mid- to late 21st century. The horizontal axis differentiates vulnerability according to type of settlement, capacity to adapt, and the mechanism through which the settlement is affected by climate change. The vertical axis identifies 12 different types of climate change impact in descending order of global importance. Vulnerabilities are rated as low, medium, or high magnitude.

Table note 2. Changnon (1996b), Yohe et al. (1996), Evans and Clague (1997), FEMA (1997), Smith et al. (1999); 2. Choudhury (1998), Rosquillas (1998), Magaña (1999); 3. Landsea et al. (1996), Pielke (1996), Pielke and Landsea (1998); 4. Yohe et al. (1996), Hurricane Mitch cost Honduras 80% of its GDP and Nicaragua 49% (FAO, 1999), Swiss Re (1999); 5. in general, wealthier areas

[6] Note that the majority of studies reviewed in IPCC (2001) and listed as sources here are not city-specific studies and are therefore not considered in detail in this literature review. Rather, the findings of these studies mostly relate to specific impacts which are applied to the generic urban context in a qualitative way.

substitute new locations from which to draw water (WG2 SAR Section 10.5.4; Changnon and Glantz, 1996; Arnell, 1998); 6. Meehl (1996), Nicholls and Hoozemans (1996), Nicholls and Mimura (1998); 7. Mimura et al. (1998); 8. FEMA (1991), Scott (1996), Rosenzweig and Solecki (2000); 9. Ren (1994), Nicholls et al. (1999), see also Chapters 6 and 11; 10. Phelps (1996), Chestnut et al. (1998), Duncan et al. (1999), Kerry et al. (1999); 11. despite acclimatization, Indian cities have lost dozens to hundreds of people to heat-related deaths in recent years—more than 1,300 in 1998 (De and Mukhopadhyay, 1998); 12. Wheaton and Arthur (1989), Rosenberg (1993), Lettenmaier et al. (1998), Gleick (2000);; 15. the 1991 Oakland Hills and the 1994 Sydney fires are examples of losses sustained at urban interface in developed countries [in Oakland, a wildfire destroyed approximately 600 ha and more than 2,700 structures in the hills surrounding East Bay, took 25 lives, and caused more than USD1.68 billion in damages (see , sponsored by the U.S. Forest Service); in the Sydney area, 800,000 ha burned, more than 200 houses—mostly in urban areas—were destroyed, and two firefighters and two civilians were killed (see Australian National University's FIRENET Web site)]; 16. EEPSEA (2000), Wheeler (2000); 17. Andrey and Mills (1999), Dorland et al. (1999), Changnon (2000); 18. for example, on the Indian subcontinent on 26 April 1989, a single severe storm—locally known as "nor'westers" or kal'boishakhi—and a tornado north of Dhaka killed 1,300 and injured 12,000; 19. Rosenberg (1993); 20. Meltzoff et al. (1997); 21. Scott (1996); 22. WRI (1999); 23. Cohen (1997), Andrey and Mills (1999); 24. Quattrochi (1996), Chestnut et al. (1998); 25. Jáuregui (1997), Chestnut et al. (1998), Lam (1999).

The recently published IPCC 4th Assessment WG II Report (Parry et al [IPCC], 2007d and Chapter 7 on industry, settlements and society Wilbanks, et al 2007) provides an update, based on more recent evidence, but reinforces the earlier findings. Additionally, it addresses vulnerability more explicitly, places climate change directly in the context of socio-economic change and recognises the potential for adaptation. The WG2 summary for policy makers (IPCC, 2007b) concludes that

> *"Costs and benefits of climate change for industry, settlement, and society will vary widely by location and scale. In the aggregate, however, net effects will tend to be more negative the larger the change in climate." and*

> *"Where extreme weather events become more intense and/or more frequent, the economic and social costs of those events will increase, and these increases will be substantial in the areas most directly affected. Climate change impacts spread from directly impacted areas and sectors to other areas and sectors through extensive and complex linkages"*

It also identifies the most vulnerable industries, settlements and societies to be generally those in coastal and river flood plains, those whose economies are closely linked with climate-sensitive resources (such as agricultural and forest product industries, water demands and tourism), and those in areas prone to extreme weather events, especially where rapid urbanisation is occurring.

The report also concludes that poor communities can be especially vulnerable, in particular those concentrated in high-risk areas. They tend to have more limited adaptive capacities, and are more dependent on climate-sensitive resources such as local water and food supplies. However, industry, settlements and society are often capable of considerable adaptation, depending heavily on the competence and capacity of individuals, communities, enterprises and local governments, together with access to financial and other resources. These conclusions are drawn with "very high confidence" by the IPCC.

2.2 Methodological issues

In contrast to the broader perspective adopted by the IPCC on climate change vulnerabilities, impacts and adaptation responses in the context of built environment and settlements, the literature review in this study has a focus on the extent to which quantification and monetisation of climate change impacts and adaptation responses has been, and is being, undertaken in city-scale impact analysis. This sub-section therefore briefly outlines a number of the principal methodological issues associated with this approach to impact analysis, and so serves to provide orientation in the subsequent discussion of the literature.

A recent European review (EEA, 2007) has highlighted some of the key aspects in the quantification and valuation of impacts at the global and regional sale as:

- Treatment of scenarios (both climate and socio-economic projections);
- Issues of valuation (market and non-market effects; indirect effects on the economy);
- The approach taken to spatial and temporal variation (discounting and distributional effects);
- Uncertainty and irreversibility (especially in relation to large-scale irreversible events); and
- Coverage (which climate parameters, and which impact categories, are included).

Many of these issues are extremely important for quantitative city level analysis as well. To illustrate: there is a need to consider different types of climate signals. As Wilbanks et al (2007) highlight the significance of gradual climate change (e.g., increases in the mean temperature or sea level rise), should be explored along with changes in the intensity and frequency of extreme events. The possible existence of thresholds, such as the capacities of infrastructures (e.g. urban drainage systems), beyond which impacts become significant, are also important to identify.

However, it should be noted that there are varying degrees of confidence attached to the modelled climate signals which, themselves, vary between models. In particular, whilst most models show broadly similar trends in average mean temperature, models can predict very different scenarios in terms of regional precipitation (even of a different sign, i.e. positive or negative) or extremes. These difficulties may be exacerbated at the city scale where down-scaling is necessary to identify city-specific impacts such as heat island effects and urban flooding, but further compounds the uncertainties surrounding the climate signals. In practice, the absence of down-scaling exercises means that most city-based studies to date have interpreted larger-scale scenarios in qualitative terms, resulting in correspondingly qualitative impact analysis.

In evaluating the literature below, these methodological issues are considered. The aim is to summarise good practice examples from across the literature, to help inform future research in this area.

3. Literature review: Empirical evidence

The literature review below incorporates empirical studies from both the academic and grey literature. This literature may be further disaggregated to include:

1. City studies/city analogue studies commissioned e.g. by city-level public authorities.
2. Country-scale studies commissioned e.g. by national environment ministries.
3. Sectoral-based studies focussed on (sub-) sectors of interest e.g. insurance, commissioned by sectoral representative bodies.
4. Academic research project reports, with greater attention on methodological development.
5. Extreme event studies i.e. commissioned following an exceptional weather event e.g. Summer 2003 heat-wave in Europe.
6. Academic journals i.e. peer-reviewed versions of studies in 1-5 above.

This review has a focus on large-city studies which include quantitative analysis. Wilbanks et al (2007) identified a growing body of assessments that have considered vulnerabilities of rapidly growing and/or large urban areas to climate change[7].

This study builds on Wilbanks et al and reviews the following studies of major global cities, listed in the table below[8].

Table 2. **Major city studies considered in current review**

City	Nature of study	Type
OECD		
Europe		
Athens	Study of future air conditioning demand for electricity from climate change. (Giannakopoulous et al, 2006)	Quantitative
Paris	Analysis of 2003 heatwave on health / infrastructure (impacts and some values), e.g. Gillet, 2006.	Historic
Lisbon	Impacts on heat related mortality with climate change (Dessai, 2003)	Quantitative
London	Several studies including economic impacts of historic extreme events, future climate change impacts, adaptation response (LCCP, 2002; 2006.) see below.	All
North America		
Boston	Climate's Long-term Impacts on Metro Boston. Transport, Energy, Health (all quantitative) and Water (valuation). (Kirkshen et al, 2006).	Quantitative Valuation
California (Los Angeles)	Heat mortality (quantitative), water availability and ecosystems under future climate (Hayhoe et al, 2004). Cayan et al (2006). Electricity. Miller al (2007)	Quantitative
Seattle	Climate Change and Seattle Department of Transportation (OCA, 2005). Consideration of recent events, and potential future multiple risks	Historic Qualitative
New York	Series of studies, e.g. Rosenzweig and Soleck et al, (2001; 2006) – quantification and valuation	All
Toronto Vancouver	Adapting To Climate Change In Toronto (health and energy) Ligeti, 2007 Climate Change Impacts and Adaptation Strategies for Urban Systems in Greater Vancouver (Sheltair, 2003) – qualitative assessment.	Quantitative Qualitative
Other OECD		
Sydney, Brisbane Melbourne	Australian GHG Office reports, as well as state studies, e.g. Victorian Government. CSIRO impact reports (e.g. Preston and Jones, 2006). Sector city studies (heath – impacts in all 10 Au/Nz cities), infrastructure (Victoria, CSIRO).	Qualitative/ Quantitative
Wellington, NZ	Climate's Long-term Impacts on New Zealand Infrastructure, Jollands et al 2006	
Mexico City, Tokyo	Disaster risk reduction in mega-cities: Making the best of human and social capital. Qualitative comparisons (Wisner, 2003)	Qualitative

City	Nature of study	Type
Non-OECD		
Cotonour, Benin	Vulnerability to Climate Change in Cotonour: the rise in sea level. Qualitative future impacts. (Glehouenue-Dossou (2006))	Qualitative
Dhaka/ Bangladesh	Flood Management and Vulnerability of Dhaka City (Huq and Alam, 2003). Alam and Rabbani (2006). Climate change induced flooding and air quality impacts (Alam et al, 2007). Historic impacts and qualitative future impacts.	Qualitative
Western Cape/	Status Quo, Vulnerability and Adaptation Assessment of the Physical and Socio-	Qualitative

[7] Wilbanks et al cite examples of cities in the developed and developing world such as Hamilton City, New Zealand (Jollands et al., 2005), London (London Climate Change Partnership, 2004; Holman et al., 2005), New York (Rosenzweig and Solecki, 2001a, b), Boston (Kirshen et al., 2007), Mumbai, Rio de Janeiro, Shanghai (Sherbinin et al., 2006), Krakow (Twardosz, 1996), Caracas (Sanderson, 2000), Cochin (ORNL/CUSAT, 2003), Greater Santa Fe (Clichevsky, 2003), Mexico City, Sao Paolo, Manila, Tokyo (Wisner, 2003), and Seattle (Office of Seattle Auditor, 2005).

[8] Note there are some additional smaller city studies, e.g. Hamilton City, New Zealand (Jollands et al., 2005), Bilboa, Spain, Halifax, Canada (Murphy et al, 2006), and regions (e.g. New Brunswick, Australian coast) that are not considered here.

Cape Town	Economic Effects of Climate Change in the Western Cape. (Midgley et al, 2005).	(for urban)
Caracas, Venezuela	Cities, disasters and livelihoods. (Sanderson, 2000)	Qualitative
Alexandria Egypt Nile	Development and Climate Change in Egypt. Coastal Resources / Nile (OECD, 2004). Sea level rise. Cost of adaptation. Water resources (not impacts).	Quantitative Valuation
Greater Sante Fe Buenos Aires	Urban Land Markets And Disasters: Floods In Argentinean Cities (Clichevsky, 2003). Assesses relationship between urban land markets and past flooding.	Qualitative
Kochi (Cochin), India	Possible vulnerabilities of Cochin, India, to climate change; impacts and response strategies to increase resilience (ORNL/CUSAT 2003)	Qualitative
Mumbai,Shanghai Rio de Janeiro	Sea level rise and temperature increase. (Sherbinin et al, 2006). Sea level rise in Mumbai (TERI, 1996).	Qualitative Valuation
Sao Paolo, Manila	Disaster risk reduction in megacities: (Wisner, 2003). Qualitative comparisons (not impacts)	Qualitative
Singapore	The impact of sea level rise on Singapore (Ng and Mendelsohn, 2005)	Valuation

The geographical locations of the above city studies are plotted on the map below.

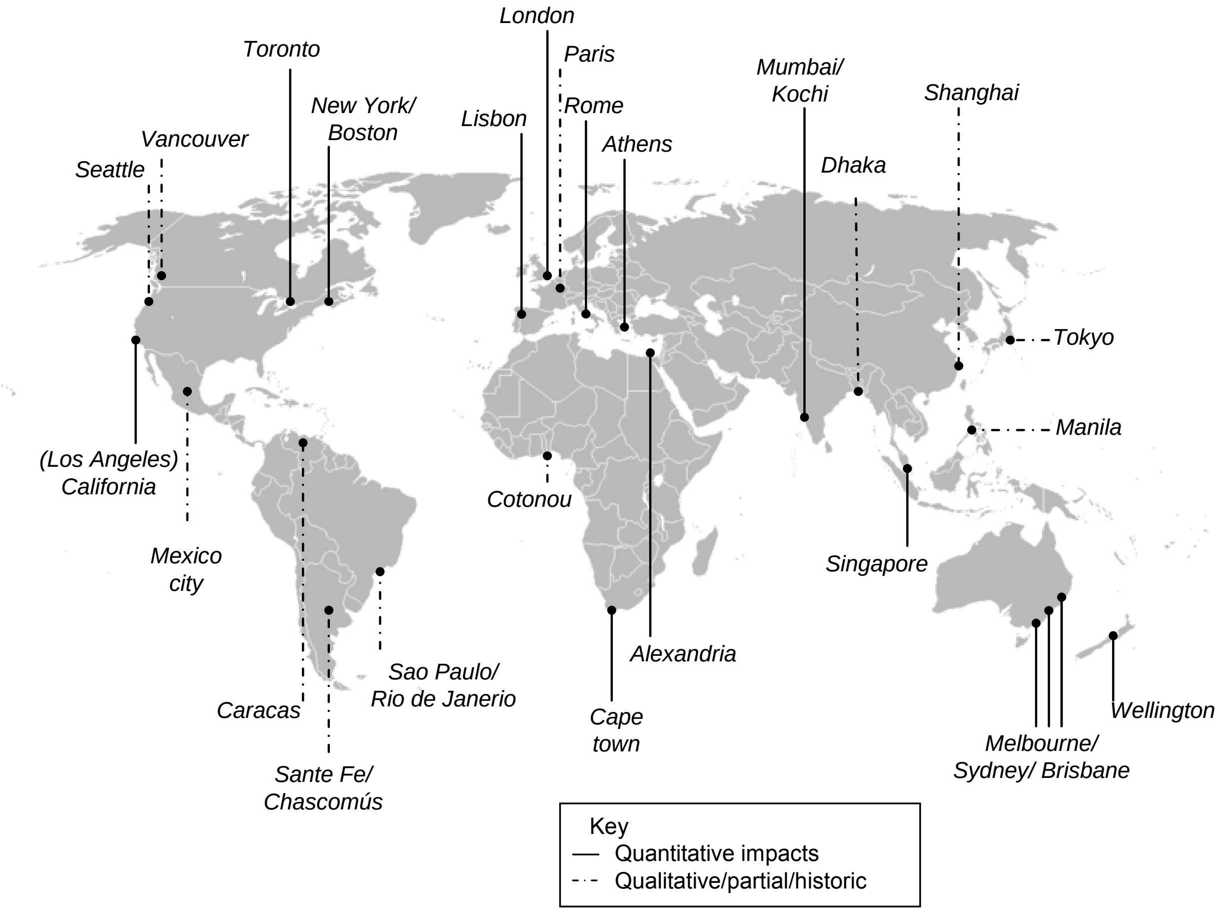
Figure 1 shows a wide coverage of locations across the continents. However, it is clear that most studies have focused on coastal cities and there is a lack of studies on inland cities. There are also a number of major regions omitted that could be important (notably cities vulnerable to hurricane risk[9] and cities subject to water scarcity in Southern Europe). Moreover, in many cases, the studies only look at a single issue (or sector), most commonly sea level rise.

This pattern of coverage is likely to reflect the fact that many major cities, and, indeed, over 50% of the world's population, are located on low lying areas or near or on coasts and so are vulnerable to sea level rise (Nicholls 2004). This should be understood in conjunction with the fact that, to date, greater certainty has been attached to the probability of sea level rise under future climate change scenarios than trends in other climate variables or impacts. The higher likelihood of this impact occurring may therefore have focussed attention research commissions. As a consequence, there are therefore clear evidence gaps on city-scale impacts of climate change across a range of geographical locations and impact categories. The current literature should therefore perhaps be seen as only indicative of the priorities of climate change faced by cities globally.

The literature review findings are summarised below first by impact category, and then on an individual city basis.

[9] There are substantial vulnerabilities to sea-level rise and coastal inundation in the southern coast of the United States. Nordhaus (2006) highlights the major concentrations of economic activity and capital (with capital stock greater than $50 billion [per 1/6 º by 1/6 ºgrid cell]) are in the Miami coast and in New Orleans for example.

Figure 1. **Geographical location of selection of major city studies**



3.1 Discussions by impact category

A brief summary by impact category is included below, highlighting city-scale impact results in the context of the more general impact literature which is predominantly sectoral. This exercise serves to demonstrate where there are likely to be significant city-scale impacts that are not yet recognised and documented in city-scale studies.

3.1.1 Coasts

Many major cities are on low lying areas or near, or on, coasts (Nicholls, 2004), and so are potentially more vulnerable to sea level rise/storm surge. Indeed, coastal cities contain large human populations and are the centre of nationally important socioeconomic activities (see Nordhaus, 2006).

McGranahan et al (2006) find that larger urban settlements tend to be more concentrated in low elevation coastal zones[10]. In all global regions, there are densely inhabited coastal areas and large cities

[10] Finding that the share of urban settlements whose footprints intersect the low elevation coastal zone rise from 24% for settlements over 100 000 population to 65% for settlements with populations over 5 million. These translate into populations of 11 and 21% respectively. The paper highlights that Asia is particularly important, due to its high overall population, but also a large proportion of this population in the zone.

that are already below normal high-tide levels, and prone to flooding from storm surges. Climate change is likely to have potential impacts on coastal cities, particularly via sea level rise and through changes in the frequency and/or intensity of extreme weather events, such as storms and associated surges. The most threatened coastal urban environments are those that lie in deltas, low-lying coastal plains, islands and barrier islands, beaches, and estuaries. Direct impacts from sea level rise include inundation and displacement, coastal erosion, increased storm flooding and damage, increased salinity in estuaries and coastal aquifers, and rising coastal water tables and impeded drainage. Potential indirect impacts include changes in the distribution of bottom sediments, changes in the functions of coastal ecosystems and impacts on human activities.

Analysis of coastal flooding is the most advanced and well covered of all the impact categories, especially in relation to the mean sea level rise, but increasingly the additional effects of storm surges. The increasing sophistication of geographical information systems allows detailed spatial analysis. There is a significant literature on the impacts and economic damages of seal level rise and coastal flooding, though much of this work is undertaken at world-regional scale. The literature includes wide ranging studies on impacts and economic costs, e.g. Nicholls and Klein (2003), Tol (2002), Deke (2002), Bosello et al (2006), Yohe et al (2006). More recently, high resolution global coastal models have been produced, for example the DIVA database and model produced from the DINAS-COASTS DG research project (DINAS-COAST Consortium, 2006; Hinkel and Klein, 2007; Nicholls et al., 2007a; Vafeidis et al., 2004; 2007) which work on (relatively) short sections of coastline.

Many of the studies in these areas include consideration of adaptation. The adaptation strategies to sea level rise include (Nicholls et al., 2007b): coastal defences (e.g. physical barriers to flooding and coastal erosion such as dikes and flood barriers); realignment of coastal defences landwards; abandonment (managed or unmanaged); measures to reduce the energy of near-shore waves and currents; coastal morphological management; and resilience-building strategies. Despite some difficulties in estimation, there is an extensive literature reporting the direct cost of adaptation to sea level rise and even estimating the optimal levels of protection at a regional level (based on cost-benefit analysis) (e.g. Tol, 2004; Anthoff et al., 2006; Richards and Nicholls, 2007, Yohe et al, 2006), and at a city level, e.g. see Kirkshen et al (2006) in Boston.

There are studies that have a city focus, including the earlier work on mega-cities (e.g. Nicholls (1995), Klein et al (2003)), and the city specific analysis of Kirkshen et al (2006) in Boston, Rosenzweig and Solecki et al (2001; 2006) in New York, Ng and Mendelsohn in Singapore, the London Climate Change Partnership in London (LCCP, 2002), Sherbinin (2006) for Mumbai, Rio de Janeiro, Shanghai, TERI (1996) in Mumbai, and OECD (2004) in Alexandria. Most of these analyses, however, do not undertake quantitative impact assessments – indeed such efforts are only now being undertaken in London alone (Hall et. al. (2005). In addition, those cities that are vulnerable in South and East Asia and Africa are not known to have undertaken specific sea-level rise impact assessments. Bigio (2003) considered cities such as Egypt; Banjul, The Gambia; Tianjin, China; Jakarta, Indonesia; and Bangkok, Thailand as likely to be particularly affected though quantitative analysis to inform adaptation decisions has not yet been undertaken. The parallel OECD study seeks to address this evidence gap.

3.1.2 Built environment and infrastructure

The main potential vulnerability to climate change of the built environment has been identified as being to extreme events; floods and storms, and to a lesser extent from heat-waves and drought[11]. In relation to these effects, there is likely to be a strong regional pattern of vulnerability, exacerbated by the

[11] Jollands et al (2005) in study on Hamilton City in New Zealand found that infrastructure systems were not very responsive to gradual climate change.

physical size of the city. Storms are currently the costliest weather events in the developed world and some research, undertaken particularly by the insurance sector, quantifies the potential future costs of climate change. For example, ABI (2005) estimated that by the 2080s, there would be a 75% increase in costs of insured damage in a severe hurricane season in the USA, a 65% increase in costs of insured damage in a severe hurricane season in Japan, and a 5% increase in wind-related insured losses from extreme European storms. Swiss Re recently estimated that in Europe the costs of a 100-year storm event could double by the 2080s with climate change (USD50/EUR40 billion in the future compared with USD25/EUR20 billion today), while Nordhaus (2006) assessed the economic impacts of U.S. hurricanes (on the Miami coast and New Orleans) and estimated that the average annual hurricane damage will increase by USD8 billion at 2005 incomes (0.06 percent of GDP) due to due to the intensification effect of a CO_2-equivalent doubling. Other estimates indicate that the cumulative contribution of changing climate risk and socio-economic development are likely to double worldwide economic losses due to natural disasters every ten years.

There are far fewer predictions of storm damage risks specifically at a city level. This may reflect the difficulty in down-scaling the prediction of extreme events to an appropriate level. The New York study by Rosenzweig and Solecki (2001) is an exception here, using historical analogues to derive annualised losses for different storm frequencies. They calculate projected damages of approximately 0.1% of Gross Regional Product, annualised, and a probable maximum loss of 10-25% of GRP for one event.

The potential risk to urban areas from major catastrophic events, e.g. as with Hurricane Katrina and New Orleans, has led to an emerging literature on the wider economic costs of such events (the indirect costs), as well as the potential for non-linear or irreversible effects, see box below [12]. The potential economic effects of extremes have long been recognised in developing countries[13], with studies which demonstrate how disasters (or particularly a series of disasters) can affect long-term economic growth. Indeed, there is now work on climate extremes with such a developing country focus[14], and a recognition that there are strong inter-linkages between climate change, adaptation and development[15]. However, while the current focus on these issues is not in the OCED, there is a growing recognition (especially post Katrina) that they could be important[16].

[12] Note Katrina did not occur as a result of climate change, though climate change may have influenced the probability of a high intensity storm hitting the area at some point.

[13] Wilbanks et al (2007: Chap 7 AR4) highlight that economic costs of extreme weather events at a large national or large regional scale, estimated as a percent of gross product in the year of the event, are unlikely to represent more than several percent of the value of the total economy, except for possible abrupt changes (high confidence), while net aggregate economic costs of extreme event impacts in smaller locations, especially in developing countries, could in the short run exceed 25 percent of the gross product in that year (high confidence).

[14] As an example, the Risk and Vulnerability Programme (RAV) being undertaken by IIASA and funded by the World Bank (http://www.iiasa.ac.at/Research/RAV/index.html) has developed the CATSIM model framework for financial disaster risk management, with a focus on developing countries.

[15] As an example, see Managing Climate Risk Integrating Adaptation into World Bank Group Operations (2006).

[16] Calzadilla et al (2006) have considered the economic implications of extreme events at global level, by region, and find indirect short-term effects (variations in savings due to higher or lower likelihood of natural disasters) can have an impact on regional economics, whose order of magnitude is comparable to the one of direct damages.

Box 2. **New Orleans and Hurricane Katrina**

There are a number of estimates of the damages of Hurricane Katrina. Nordhaus (2006) cites damages of USD81 billion, the 4th Assessment Report estimates total economic costs are projected to be significantly in excess of USD100 billion.

However, a number of studies have considered the wider economic effects of this event. In a recent analysis, Hallegatte estimates that the full macro-economic costs of Hurricane Katrina in New Orleans were roughly 25% more than direct costs alone, bringing related damage costs for this incident to roughly USD130 billion (Hallegatte 2007 forthcoming). The significance of these estimates is put in perspective when compared to the size of the Louisiana gross domestic product, which stood at about USD168 billion in 2005. Other studies find even larger macro-economic costs [e.g. Kemfert (2006) reports full macro-economic costs of Katrina were double direct costs, from the additional effects of oil price increases, increased energy costs, and other factors].

Wibanks et al, 2007 highlight that reconstruction costs have driven up the costs of building construction across the southern U.S., and federal government funding for many programmes was reduced because of commitments to provide financial support for hurricane damage recovery.

Storm risk is not the only concern. Recent climate modelling projections suggest that in the coming decades global warming will intensify the hydrological cycle and increase the magnitude and frequency of intense precipitation events. Flood hazard may also rise during wetter and warmer winters, with increasingly more frequent rain and less frequent snow (though spring snowmelt floods are likely to reduce (Kundzewicz et al., 2006). Detailed regional modelling of river catchments is now emerging with analysis of impacts and economic costs, e.g. Feyen et al (2007) who estimate that the total damage of a 100-year flood in the Upper Danube will rise by around 40% of the current damage estimate (an increase of EUR18.5 billion) by 2100 under the high emission scenario (A2) and around19 % for the low emission scenario (B2) by 2100. It is noted, however, that the observed upward trend in flood damage can be attributed to socio-economic factors, such as the increase in population and wealth in flood-prone areas, to changes in the terrestrial system, such as urbanisation, deforestation and loss of natural floodplain storage, as well as to changes in climate.

A number of historical analogues of city-scale flood events have been costed. For example, Compton et al (2002) found four cases when flooding of urban underground rail systems have caused damage worth more than EUR10 m (USD13m) (in Prague, Boston, Seoul and Taipai) and numerous cases of lesser damage in the last ten years (in New York, Fukukoa Japan, in Caracas in Venezuela and in Santiago in Chile). The scenario-based impact work for Boston (Kirshen et. al. (2004) reported above, estimated that total losses throughout metropolitan Boston from river flooding will exceed USD57 billion by 2100 assuming no adaptive steps are taken, of which USD26 billion is attributed to climate change. Under a pro-active adaptation strategy, this was forecast to reduce from USD26 billion to an estimated USD9 billion by 2100. There is, indeed, a strong role for adaptation as a response to all extremes. The additional costs of making new infrastructure and buildings more resilient to climate change (though this includes resilience to all climate effects not just storm damage) in OECD countries could range from USD15 – 150 billion each year (0.05 – 0.5% of GDP), with higher costs possible with the prospect of higher temperatures in the future (Stern, 2006)[17]. However, greater disaggregation of such totals is likely to

[17] Infrastructure is particularly vulnerable to heavier floods and storms, in part because OECD economies invest around 20% of GDP or roughly $5.5 trillion in fixed capital each year, of which just over one-quarter typically goes

be more useful in future as individual city administrations attempt to scope, and subsequently address, the risks to the built environment by geographical location and accounting for site specific conditions.

3.1.3 Energy

Energy demand is linked to climatic conditions, with climate change likely to lead to changes in demand for winter heating and summer cooling. As a general statement, there is likely to be a decrease in the demand for winter heating, but an increase is summer cooling (which can be described as either an impact or an adaptation), though the scale of these effects is strongly determined by the climatic zone and also socio-economic conditions. Recent studies (see Downing et al, 2005) indicate that energy demand is the most important category in many of the existing integrated assessment model, dominating the overall economic (social) costs of climate change.

However, the net economic effects for most major OECD regions (at least in Europe and the US) are predicted to be modest in the short-medium term, due to the aggregated effects of lower winter demand vs. higher summer energy demand. At a more dis-aggregated scale, the geographical and climatic location will show strong distributional patterns: using Europe as an example, there are predicted to be strong increases in cooling (electricity) demand in summer particularly in Southern Europe, but reduced heating (energy) demand in winter, particularly in Northern Europe (EEA, 2007b). Similar results are founding the US (Hadley et al 2006) and Japan (IPCC, 2001) [18]. Moreover, these changes may be exacerbated by the type of energy sources, as winter heating demand is more associated with primary fossil fuel use, whilst summer cooling is associated with electricity demand (and so may imply higher marginal costs and be more important in economic terms than the energy balance alone suggests, especially in locations where peak electricity demand is in the summer[19]).

These issues can be particularly important at the city scale. First, because of the concentration of business and industry in cities (and so the dis-proportion use of energy in urban locations), and second because of additional factors such as urban heat island effects, especially for major cities, which have the potential to exacerbate cooling demand (note also that there is a future potential feedback to the urban heat island effects from the greater use of air conditioning). These issues are already being recognised at the city scale, and Tokyo for example, already has heat maps of the city. A number of the city studies have started to progress further towards quantified assessments of the likely changes in energy demand. Examples include:

- In Athens, Giannakopoulous (2006) estimated a 30% increase in energy demand by 2080 during July due to air conditioning.

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into construction. The preliminary cost calculation in Stern assumes that adaptation requires extra investment of 1 – 10% to limit future damages from climate change.

[18] Hadley et al (2006) found changes in USA energy-use through year 2025 for a low (1.2°C) and a high (3.4°C) temperature response to CO2 doubling. The low scenario had a cumulative (2003–2025) energy increase of 1.09 quadrillion Btu (quads) for cooling/heating demand. Northeastern states had net energy reductions for cooling/heating over the entire period, but in most other regions energy increases for cooling outweighed energy decreases for heating. The high-ΔT scenario had significantly increased warming, especially in winter, so decreased heating needs led to a cumulative (2003–2025) heating/cooling energy decrease of 0.82 quads. In both scenarios, CO2 emissions increases from electricity generation outweighed CO2 emissions decreases from reduced heating needs. For the north-south orientation of Japan, IPPC (2001) cites Ichinose (1996) that for Japan that reduction in heating would be about 30% in Sapporo on the northern island, whereas it would be only 10% in Tokyo on the central island of Honshu – but electricity consumption for cooling would increase in the southern island of Okinawa.

[19] These may be exacerbated by extreme events (e.g. heat waves) and the peak daily requirements through air conditioning.

- In London, the typical air conditioned office building is estimated to increase energy used for cooling by 10% by the 2050s, and around 20% by the 2080s (LCCP, 2002).

- In Toronto, an average temperature increase of 3°C in Toronto was found to be associated with a 7% increase in mean peak electric demand, but a 22% increase in the peak electric load standard deviation (Colombo, Etkin et al. 1999).

- In Boston, Kirshen et al, 2006 used regression results with various climate change scenarios to project future energy use and estimated that by 2030, the average number of days in July requiring air conditioning could increase by over 24% with a corresponding rise in energy use (and that by 2030, climate change will be responsible for 25-40% of increased energy demand in the region). They also commentated on the reduction in winter heating, but highlighted that while overall winter/summer energy use may not change significantly in overall physical energy terms, there could be significant consequences from the large capital costs to expand the electric energy system for cooling.

- In California, Miller al (2007) have predicted that extreme heat events in California will increase rapidly, exceeding the rate of increase in mean temperature. The number of extreme heat[20] days in Los Angeles may increase from the current levels of 12 days per year up to 96 days per year by 2100, implying current heat wave conditions may last for the entire summer. In California, residential peak electricity demand by mid-century is projected to increase by 2.8%–10.0% under the A1fi and A2 scenarios and by 3.4%–7.7% under the B1scenario. By the end of the century, this demand is projected to increase by 6.2%–19.2% under the A1fi and A2 scenarios, and by 4.0%–11.2% under the B1 scenario. These findings, combined with observed relationships between high temperature and electricity demand for air conditioning, suggest potential shortfalls in transmission and supply during more frequent future peak electricity demand periods, and may be further challenged when population and income growth are taken into account. However, the potential for adaptation could be significant, potentially reducing projected increases in electricity demand by roughly one third for inland cities, and by as much as 95% for cooler coastal cities.

It is clear that these effects will be more important in hotter climates – for example IPCC (2001) reports that space cooling is already a major concern in tropical and subtropical cities, reporting that it accounts for as much as 60% of total electricity use in the commercial sector in Hong Kong, and a similar level of all electric energy in Riyadh, whilst Miller et al (2007) report that in 2004, 30 percent of California peak electricity demand was attributable to residential and commercial air conditioning use alone. There may also be an emerging issue of energy use rising for water supply (pumping, desalination, recycling, water transfers), that again may be concentrated in certain climatic regions, as well as the issue of water availability for hydro-electricity in some regions. However, in more temperate regions, these effects need to be compared against likely benefits from reductions in winter heating demand (though as highlighted above, the decrease in winter energy demand involves different issues to an increase in summer peak electricity, not least due to power capacity and infrastructure).

There are complex issues in predicting future energy demand and prices, not least because of the need to predict future energy and electricity prices (under socio-economic conditions and future mitigation scenarios), and because of the complex relationships between penetration (strongly income and energy price dependent, but also influenced by extremes) and technological efficiency.

[20] 90 per cent exceedance probability (T90) of the warmest summer days under the current climate. In Los Angeles this is currently 95°F.

Adaptation has a role to play here – particularly through alternatives to mechanical air conditioning, e.g. through passive ventilation, building design, planning, green roofs, etc. and is the subject of an emerging set of design guides (e.g. Shaw et al, 2007)

Overall, and despite its potential importance, the evidence on the economic effects of energy use are rather limited, restricted to studies mostly in relation to quantification (rather than monetisation) in a few locations. A broad range of impact approaches have been used, with econometric analysis, but also response functions. This is certainly a complex area to predict, with strong links to the underlying socio-economic and mitigation scenarios, but is highlighted as a research priority. Unlike the analysis of floods and extremes above, it is also defined by mean temperature change (though can be exacerbated by extremes). This means the confidence in the impacts is high (though predictions remains challenging). The cumulative effects of gradual temperature change (mean average) will therefore lead to significant economic effects, though a combination of climatic location and existing energy structure, demand and prices (for different energy sources) will dictate the net physical changes and the net economic effects (which will differ).

As an example, annual expenditures of electricity demand in California represent about USD28 billion (see Cayan et al, 2006) and so even relatively small increases in energy demand predicted would result in substantial extra financial expenditures for energy services. Under a high warming scenario (e.g. Cayan et al[21] cite that a 3% increase in electricity demand by 2020 would translate to about USD1.2 billion nominal dollars a year in additional electricity expenditures – under an A1f1 scenario, by 2100, they predict that annual (and peak) electricity demand might rise by 20%). Cumulatively over time, these will clear have significant economic effects that are as large as categories considered above.

3.1.4 Health

Climate change is likely to affect human health, either directly from the physiological effects of heat and cold, or indirectly, for example, through the increased transmission of food-borne or vector-borne pathogens, or through the wider effects on well being from flooding. There are estimates of the global effects on health from climate change by world region, notably the WHO global burden of disease (McMichael, 2005). In OECD countries, this is an area of concern, particularly in relation to heat related mortality, not least because of the observed impacts in Europe (e.g. the summer heat waves in 2003 alone claimed more than 35 000 excess deaths: EEA 2004). However, whilst there are likely to be increases in heat related mortality, these need to be balanced against the decreases in cold related mortality that will also occur with climate change. Indeed, there is some uncertainty over the net effects (the sum of heat and cold effects) for OECD countries, and especially the distribution of benefits across the more temperate regions of Europe or the US. As an illustration, the recent European PESETA project (AEA, 2007) quantified and monetised the effects in Europe and found large economic costs (billions/year) from summer mortality by the 2080s, but similar or larger economic benefits from the reduction in winter mortality.

There are some specific issues at the city-scale, notably the increased risk of heat extremes associated with heat-waves and the urban heat island effects. As a result, there is already a body of literature emphasising, in qualitative terms, the health effects of current heat extremes (and cold extremes), with major city studies in all regions and for most major cities. There is less quantitative analysis, however, of future effects with climate change though there are several major city studies: as highlighted above, empirical projections exist for Lisbon (Dessai, 2003) Los Angeles, (Hayhoe et al (2004)), New York, (Kinney, et al (2006), Boston, (Kirshen et al, 2006), a group of 10 Australian and 2 New Zealand

[21] See also supporting annex by Guido Franco and Alan H. Sanstad
http://www.climatechange.ca.gov/climate_action_team/reports/index.html#supporting

cities, (McMichael et al (2003)) and 11 Eastern US cities (Curriero et. al., 2002). These studies project increased average annual morbidity and mortality impacts, though the study of Boston illustrates that with appropriate adaptation measures, any increases may be negated.

There is clearly a strong geographical and climatic variation to these effects, but the analysis is complicated by acclimatisation: populations will partly acclimatise to future temperatures, and there is also the potential for adaptation beyond this, for example with the current heat alert systems. It is also highlighted, however, that heat related health concerns themselves are likely to drive interactions with energy use and air conditioning.

In addition to these temperature related events, climate sensitive infectious diseases, such as Salmonella, have the potential to increase under a changing climate. Some emerging work (AEA, 2007, based on Kovats, 2003) shows that the disease burden in Europe could be significant, and have a potentially high social costs (potentially several billion Euro a year by the period 2070-2100 through medical costs, lost time at work, willingness to pay to avoid pain and suffering, and through the small number of cases of food poisoning that are fatal), though adaptation offers a low cost means to reduce these. The increasing intensity of heavy rainfall is likely to make extreme floods more frequent in some areas (see below). While the number of deaths and injuries from floods are relatively low in OECD countries, flood events do have important wider effects, notably in wider well bring (mental health and stress and depression (e.g. see Reacher et al, 2004). There is some emerging quantification and valuation of the latter well-bring effects, which show that without adaptation, baseline risks, health effects and costs could be significant. However, coastal and river flooding adaptation should reduce these very significantly. Against these potentially negative effects, there may be some benefits for wider health and well being (especially in mid and upper latitude areas) which include reduced cold related illness and wider quality of life benefits. These additional health effects are potentially important in cities – either because of the population size or, in the developing country context, because of the greater vulnerabilities resulting from e.g. current low standards of health care provision.

Data on the costs of surveillance and outbreak control (adaptation costs) are starting to emerge and there are adaptation strategies that can be implemented by health sectors (e.g. see the cCASHh project in Europe), most of which are likely to build on well-established public health approaches, though further work is needed to fully assesses the costs of adaptation. There are already a series of heat alert systems in place in major cities, e.g. Paris, Toronto, Montreal, etc, which are appear very cost-effective. This reflects a general indication that most adaptation measures for health appear to be low cost (e.g. provision of information), though there is the potential for some to involve more costly large-scale vaccination or other prevention programs against vector borne disease. Some recent studies have considered the potential direct and indirect costs of health care (e.g. Bosello et al, 2006) and show that these are likely to be relatively small for Europe and the USA in terms of GDP, but potentially important in developing regions.

Overall, this is an area where quantification is well advanced (though there are far fewer studies that assess economic costs). The focus has been on heat and cold related mortality, and there is clearly strong spatial and geographical variation in relation to the balance between heat and cold related mortality changes. Some of these changes can be counter-intuitive (e.g. some studies predict greater heat related mortality in areas that are currently temperate than those that are already hot, due to the low levels of existing adaptation in the former), and the role and rate of acclimatisation is important – both in relation to existing but also a changing climate. There is also a wide range of impact assessment methods based around average vs. extremes for heat, thresholds of effects, response relationships, etc. Further work is needed on the wider suite of health effects.

3.1.5 Water

Climate change has the potential to affect water demand, as well as water availability. Increases in average atmospheric temperature will accelerate the rate of evaporation and demand for cooling water in human settlements (IPCC, 2001), thereby increasing overall water demand, while simultaneously either increasing or decreasing water supplies (depending on whether precipitation increases or decreases and whether additional supply, if any, can be captured or produced (e.g. through desalinisation). OECD countries or regions have a very diverse hydrological pattern, but there are some projections of regional vulnerabilities. Kundzewicz, et al (2007, WGII) conclude that semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater (high confidence). This includes a number of major OECD regions (e.g., Mediterranean basin, western USA) as well as developing country regions (southern Africa, and north-eastern Brazil), which will suffer a decrease in water resources due to climate change

Changes in water demand strongly depend on economic growth and societal development, as well as patterns of demand change from other sectors. Economic sectors which are projected to be most affected are (EEA, 2007c): agriculture (increased demand for irrigation), energy (reduced hydropower potential and cooling water availability), health (worsened water quality), recreation (water-linked tourism), fisheries and navigation, as potentially serious impacts on biodiversity.

Working Group II (IPCC, 2007) highlights that any change in climate that reduces precipitation and impairs underground water resource replenishment would be a very serious concern for some human settlements, particularly in arid and semi-arid areas, in settlements with human-induced water scarcity and in regions dependent on snowpack and glaciers. There may also be issues of water quality in areas where river flows decrease.

Analysis of the effects on water resources are more complex to undertake, requiring detailed catchment level information along with detailed climatic predictions. Not surprisingly there are fewer studies, despite the potential importance of this issues. There are even less studies at the city scale and most studies tend to look at overall water availability and responses to falls in availability, rather than trying to predict potential impacts. Apart from those documented above, exceptions include Washington DC, (Boland (1997)) where, using several climate transient forecasts for the year 2030 there are estimated increases in summertime use of 13 to 19% and annual use of –8 to +11%, relative to a future increase from 1990 without climate change, (and as a result of socio-economic change), of approximately 100%. In Nagoya, Japan, Shimizu (1993, quoted in Mimura et al., 1998) estimated that daily water demand would increase by 10% as the highest daily temperature rose from 25 to 30°C. There are very few studies monetising impacts and adaptation (other than on the potential costs of providing additional water supply, usually through engineering solutions). However, there is some regional work in the UK that has assessed and valued water resource impacts: Wade et al, 2006 estimated that the economic losses to households of foregone water use due to the anticipated water deficit by 2100 in south-east England could be between GBP41 and GBP388 million a year (depending on scenario), but that the costs of largely (but not entirely) eliminating these deficits would be only GBP6 to GBP39 million/year (effectively the costs of adaptation).

Adaptation to changes in total water availability at a city scale is starting to gain attention in the literature. Rozensweig et. al. (2007), outlined below, report the development of a sophisticated analytical response to a projected fall in water availability in New York, that frames adaptation assessment within a step-wise decision analysis, first identifying and quantifying impact risks before identifying adaptation options that are then screened, evaluated and finally implemented. Mukheiber and Zievogel (2007) also outline a potential framework to develop a Municipal Adaptation Plan (MAP) for Cape Town that addresses urban water supply, as well as flooding, fires and coastal erosion whilst Muller highlights possible adaptation options to meet projected short-term shortfalls in water availability in Johannesburg

(Muller, 2007). There is also some regional work that covers major cities, e.g. the work Hayhoe et al (2004) and later Cayan et al (2006) drew attention to the fact that since there is a significant projected decline in runoff and streamflow from the Sierra snowpack, and that California's current water rights system may have to be re-designed. Nevertheless, there remains considerable uncertainty in the climate models in relation to both average precipitation (note in some cases, different models not only predict regional precipitation levels that vary significantly in size, but also in sign) and also extremes in relation to drought. Further advances are probably needed in the modelling and down-scaling but further work to consider the potential economic consequences (e.g. through case studies) are warranted.

3.1.6 Tourism and cultural heritage

With growing income and increasing leisure time, the OECD tourism industry is expected to continue to grow. There are now studies of regional and global tourist flows from climate change. These show potentially important changes, with strong distributional (climatic) patterns. Work by Hamilton and Tol, (2006), using a temperature-based index of attractiveness, shows that for most OECD countries and scenarios the number of inbound tourists increases. Population growth and economic growth in the rest of the world cause the shift in the balance. The impact of climate change is either to increase the rate of growth – for example, increasing the relative levels in more temperate countries. There will also be changes in domestic tourism, reflecting how countries become more or less attractive for domestic trips. Other factors apart from mean temperature are also likely to play a role in influencing visitor number in practice. For example, water shortages due to extended droughts may affect tourism flows in some regions, as may be the case in southeast Mediterranean where the maximum demand coincides with the minimum availability of water resources. More frequent and intense heat-wave conditions may also dissuade visitors from parts of Southern Europe during the summer. In addition, coastal-based tourism may also be affected by increased coastal erosion resulting from sea level rises.

Some care must be taken in interpreting these changes, as city tourism is not always as dominated by climate, indeed a significant part of city tourism revenues come from short-breaks (certainly within domestic and near neighbour markets), but cities often act as major gateways for international tourists and through affects on wider tourist assets, these could have important effects.

There is also an issue of cultural heritage and the potential threat of climate change (which includes but is wider than tourism alone). This is an emerging area, though it is clearly important for many major cities. As an example, there has been analysis of the potential impacts of climate change in Venice, with emerging valuation studies (Breil et al, 2005), which show that even very modest sea level rise in the absence of policy protection could lead to increased costs.

The effects of climate change on tourism are emerging as a potentially important impact area, at least in respect to the likely distribution of effects. There are a number of impact and valuation studies, that these are constrained to a country level. They have some relevance in the city context, though city tourism is a relatively low share of the overall sector. The issue of cultural heritage does have potentially important resonance at the city level, though there are very few studies – this is seen as an area worth investigating further.

3.1.7 Urban biodiversity

There are potential impacts on urban ecosystems or biodiversity (and the quality of the urban environment), but also nearby natural resources, which could affect recreational as well as other aspects (resource availability, protection, etc). These effects are small in relation to the wider concerns on ecosystems, and have received relatively little attention. The analysis is also complicated by the difficulties in quantification (and especially monetisation) of these effects. Few city relevant studies have been undertaken. There is a study for Singapore (Ng and Mendelsohn, 2006) which looked at the economic impact of sea-level rise on non-market lands (beaches, marshes and mangroves) using travel cost and contingent valuation studies. At the very least these studies demonstrate that inhabitants attach considerable value to beaches and natural resources (but that protecting non-market land uses from sea-level rise can be expensive, though justified in the case of highly valued resources). Overall, there remains a lack of quantitative data, and a major gap on quantitative economic analysis for ecosystem loss, though this is not as great a priority (at the city-scale) as the other areas above.

3.1.8 Air pollution

Whilst air pollution levels have reduced significantly in recent decades in OCED cities, the health risks of air pollution are still significant. Climate change has some potential to affect air pollution, though these changes will be strongly determined by the future air quality policy and also climate policy (e.g. in relation to the changes in baseline air emissions, and the changes that will occur through mitigation scenarios). The effects of climate change are most likely to be important in relation to ozone – a major pollutant in the USA and also some parts of Europe[22], as well as Australia and Mexico. Ozone (O_3) is a photochemical oxidant. It s a secondary pollutant formed in atmospheric chemical reactions between hydrocarbons (or VOCs) and oxides of nitrogen (NOx) in the presence of sunlight. There is, however, limited empirical evidence, the main exception being the study undertaken by Knowlton et. al (2004) for the New York metropolitan area, which projects increases of 4.5% in mortality rates for the 2050s, due to O_3-related acute impacts from climate change alone.

The quantification of the impacts and economic costs of air pollution, per se, is well advanced in relation to many areas of environmental economics, but the linkages between climate change and air pollution are only starting to emerge. Even recent studies on air pollution (e.g. in Europe) have not factored in how climate change might influence air quality levels. This is seen as a priority area for advancing these linkages.

3.2 City level analysis

The most quantitatively advanced studies for the city level that have been found are those for London, New York, Boston and Los Angeles (strictly speaking for California): though even here the coverage is partial. By way of illustration, we discuss the studies undertaken for London and New York in some detail, before providing a shorter summary of results from the range of other major city studies. The studies focussed on London and New York are listed in Table 3.

[22] In Europe, particulate air pollution is currently the greatest health concern. The effects of climate change on particulate concentrations is unclear: air pollution episodes are associated with anti-cyclonic conditions, and whilst these may increase in summer, they may also decrease in winter). Note that some US studies (e.g. Cayan et al) report that whilst ozone levels may increase with climate change, particulate concentrations may decrease, though this is complicated by other changing factors (e.g. global ozone, see Drechsler et al (2006).

Table 3**. Study references for studies relating to climate change impacts and adaptation: London & New York**

City	Reference	Primary purpose	Funder
London	LCCP, 2002	Scoping study of CC impacts and adaptation options	London Climate Change Partnership
	GLA, 2006	Analysis of London's urban heat Island effect	Greater London Authority
	LCCP, 2006a	Review of adaptation options utilised in other cities	London Climate Change Partnership
	LCCP, 2006b	Adaptation options in financial services sector	London Climate Change Partnership
	City of London, 2006	Adaptation strategy for City of London	City of London Corporation
	LCCP, 2005	Impacts on Transport Systems and adaptation options	London Climate Change Partnership
	Kovats et. al. 2003	Health effects of heat waves	European Commission
	The Mayor of London and the Environment Agency, 2007	Draft regional Flood Risk Appraisal	Greater London Authority and Environment Agency
	Environment Agency, forthcoming	Tidal flood risk management plan for London and Thames estuary	Environment Agency
New York	Rosenzweig and Solecki, 2001a	Scoping study of CC impacts and adaptation options	US National Science Foundation, Columbia Earth Institute and US EPA
	Knowlton et. al. (2004)	CC-induced Ozone-related health impacts	STAR Grant, US EPA
	Rosenzweig et. al. 2005a	Measurement of Urban Heat Island in New Jersey	US EPA, New Jersey Department of Environmental Protection
	Solecki et. al. 2005b	Mitigation of Urban Heat Island in New Jersey	US EPA, New Jersey Department of Environmental Protection
	Kinney et al, 2006	Heat-wave and ozone-induced health impacts	US EPA
	Rosenzweig et. al. 2007	Adaptation assessment in NY water supply, sewer, and wastewater treatment systems	New York City Department of Environmental Protection, New York City Water Board, and Columbia Earth Institute

The methods and findings are summarised in Table 4.

Table 4. **Summary of key findings from scoping studies**

City/Study	Selection of Principal Outputs
London	(LCCP, 2002) Historical cost analogues: Autumn 2000 floods - >GBP 1 billion to UK Industry - GBP 1 million to rail users 2003 heat wave - > GBP 0.75 million to rail users 1987 wind storm - GBP 1.5 billion Projected future impacts, Using down-scaled HadRM3; 50 km grid interval UKCIP02 CC scenarios, plus catastrophic event (1 metre SLR): Qualitative impact identification split into environmental, social and economic impact categories. Economic impacts summarised by indicative scale of severity, employment effects, degree of uncertainty, sensitivity to socio-economic change, key non-CC drivers of change, and availability of adaptation options. Selected impacts include: *Urban heat island* effect e.g. 20% increase in cooling energy by 2080s *Flooding* – increases in future return periods for tidal, drain and river flooding *Water resources* – supply imbalance, subsidence Treatment of adaptation Identification of options and potential institutional responsibilities. Selected examples include: *Temperature increases*: building design (including use of shading, efficient cooling and natural ventilation, green roofs) and emerging planning responses (heat-wave plans). *Flood risks*: improved flood forecasting and warning, promotion of flood proofing of buildings, accelerated investment in flood management, and addressing future development (at least to ensure adequate flood protection is in place). On-going work to develop a flood management plan to 2100. *Water availability*: various innovative water resource options, hard engineering (reservoirs), water efficiency, metering, building design, leakage control, and awareness raising
New York	(Rosenzweig et. al. 2001) Climate scenarios constructed using either a) plausible sensitivities that capture changes to existing climatic variables, b) extending existing trends in climatic data, and c) projections based on global climate models (GCMs). 5 scenarios adopted included: current trends; Hadley GHG (HadCM2); Hadley GHG + sulphate aerosols; Canada GHG (CGCM1); Canada GHG + sulphate aerosols. Projected future impacts Focussed on: *Sea-level rise and coasts* - SLR by 25 – 105cm by 2080s and reduced flood return periods. Consequent flooding of 2/3 of built infrastructure ≤ 3 metres above sea-level at least once per decade by 2100. Storm costs projected to be USD100-300m annually; with mega-storms causing USD100 billion. *Wetlands* - Inundation of salt marshes and habitat disruption. *Water supply* - Disruption of watershed ecosystems and general increased variability of hydrological systems. *Public health* - Increases in summer heat stress morbidity and mortality; vector and water-borne disease prevalence may increase; increases of 2.5% and 6.5% in annual hospital admissions for total respiratory causes and asthma, respectively, from climate-induced ozone concentrations. *Energy demand* - Air conditioning to increase daily peak load 7-12% in the 2020s, 8 to 15% in the 2050s and 11 to 17% in the 2080s, putting stress upon the electricity system during summer heat waves. Treatment of adaptation Range of potential adaptation responses available to mitigate the adverse impacts of climate change in each sector, and can effectively be introduced as long as there is increased institutional co-operation. 9-step Adaptation Assessment procedure (from Rosenzweig et. al. 2007). Identify risk; Identify main climate change impacts to that project; Apply future climate change scenarios; Characterize adaptation options; Conduct initial feasibility screening; Link to capital cycles; Evaluate options: e.g., benefit and cost analysis; Develop implementation plans, including timeframe for implementation; Monitor and reassess. Potential climate change adaptations are divided into management, infrastructure, and policy categories, and are assessed by their relevance in terms of climate change time-frame (immediate, medium, and long term), the capital cycle, costs, and other impacts.

Both initial scoping studies arose in the late 1990s out of national initiatives – the UK Climate Impact Programme regional scoping exercise and the US Global Change Research Program - within the UK and the US respectively, to scope the impacts of climate change at the regional level. In both countries these were the first city-based studies. However, whilst the New York scoping study was funded from the national budget by US EPA, the London scoping study was funded by a consortium of stakeholders, including the Greater London Authority, known as the London Climate Change Partnership. Subsequent sectorally-focussed research has almost entirely been funded by local public authorities. Reflecting this, these initiatives are, in both countries, now being taken forward by dedicated organisational structures – the London Climate Change Partnership; the New York City Department for Environmental Protection Climate Change Task Force – charged with co-ordinating cross-institutional adaptation responses.

Tables 3 and 4 above give an indication of the range of activity undertaken (and continuing) in London and New York relating to the analysis of climate change impacts and adaptation. The pattern of initial scoping studies – primarily of the likely potential climate change impacts, but also of indicative implications for adaptation actions – followed up by more focussed studies that focus on prioritised impacts and the development of adaptation plans is common to both cities. In the case of London the foci of the more detailed analysis includes work on the transport sector, flood risks and health risks from the urban heat island effect. The focus on transport and flood risks may be seen to reflect priority issues in the city's short-to-medium term development plans i.e. modernisation of the rail and underground networks and the Thames Gateway housing development projected to accommodate an additional 160,000 houses by 2016. The focus on the urban heat island in both cities reflects its distinct, and exacerbated, nature in cities of such large size. As with London, the other foci in New York, on health and water resources, arise from infrastructural investment priorities in the city, stemming from short-term socio-economic pressures.

The two scoping studies, both using a mix of desk-based study and stakeholder consultation approaches, frame the impact research in terms of the quantitative outputs – weather variable means and extremes - from established climate scenarios, subsequently down-scaled. In the main, the impact analysis based on these scenarios is qualitative, describing plausible types of sectoral impacts. Quantitative physical estimate ranges were, however, made in the New York study for some impacts in public health, sea-level rise and energy demand (see Table 3 above). In addition, the London study provides estimates of the physical impacts and economic costs of a number of historic extreme events, as well as projections of future impacts (and indicative estimates of future economic costs) from these events that are likely to become more frequent under current climate change scenarios.

In the series of studies in both cities, stakeholder involvement primarily informs the possible responses to climate change impacts. In London, research (LCCP, 2006a) also draws upon comparative analysis that identifies adaptive measures now used in cities that currently experience similar climate conditions to those projected for London under climate change scenarios. However, the uncertainty that resides in impact analysis, e.g. from the range of conditions under alternative climate change scenarios, has so far tended to deter sectoral adaptation analysis away from probabilistic scenario-based quantification and towards the pursuit of adaptation options that will be beneficial even in the absence of climate change. For example, City of London, (2006), categorises all identified adaptation options as either no-regret, low-regret, win-win or flexible. The resulting options are then expressed qualitatively; for example, for managing flood risks, a suggestion is that "The City of London Corporation should consider installing sustainable drainage systems, green roofs or green walls on City of London Corporation-owned car parks and buildings when they are refurbished or replaced". This example also serves to illustrate a key feature of much of the work on adaptation, which is to identify the principal actors likely to be engaged in implementation of specific adaptation actions.

The example from City of London (2006), above, also serves to illustrate the mainstreaming of climate change adaptation decision-making into current investment cycles. This process has been further formalised in the analysis of the water resource sector in New York, (Rosenzweig et. al. 2007), where the stepped assessment procedure for adaptation outlined in Table 3 is developed within a context where a mature infrastructure system exists, where its managers are skilled at dealing with existing hydrologic variability, and where there are many potential adaptations to the risk of climate change in the NYC water supply, sewer, and wastewater treatment systems. Since quantitative modelling of existing hydrologic variability, quantitative analysis of climate change impacts – imposed on projected socio-economic change – is being developed.

Thus, daily and monthly temperature and precipitation results from the GCM simulations chosen for the regional scenarios are downscaled for the NYC watershed and urban region. Sea-level rise estimates are taken from the applicable GCM model grid and adjusted as needed for local subsidence, thermal expansion, and freshwater influx. Other GCM outputs, such as specific humidity, solar radiation, and windspeed that are relevant to the NYC water supply, sewer, and wastewater treatment systems are also downscaled from the grids. Depending on the outputs from the subsequent hydrological modelling it is intended that potential climate change adaptations - divided into management, infrastructure, and policy categories – should be assessed by their relevance in terms of climate change time-frame (immediate, medium, and long term), the capital cycle, costs, and other impacts. Whilst quantitative decision analysis has not been reported to date it is understood that with regard to e.g. appraisal of new infrastructure, detailed cost-benefit studies are planned to estimate net benefits and reduce fiduciary risk.

Whilst the work in these cities is evolving quickly it seems apparent that the need for quantitative analysis is dependent on the existing practices with regard to formal decision-making practices. Thus, investment appraisal in e.g. transport (London) and water supply (New York) appear to be principal areas where quantitative analysis will be undertaken. It is notable, however, that quantitative analysis is limited at the aggregate city-scale in these examples, suggesting that there remains outstanding potential for it to be used in a more strategic, influencing, way within the cities' administrations, and beyond.

The two cities, London and New York, are global mega-cities with substantial economic national and international importance, though both having assets and operations potentially at risk from projected climate change. It is interesting to note that e.g. in terms of being financial market centres they can be viewed as competitors with each other (as well as with other cities such as Tokyo). Indeed, the London scoping study makes this competitiveness explicit by developing an index of attractiveness against which it attempts to evaluate how climate change impacts may affect its competitiveness vis-à-vis New York. In common with each other, and as opposed to previous work with a city focus, the scoping phase of work addressed a wide range of potential sectors and types of impacts from changes in climatic means as well as extremes.

3.2.1 Other city studies: OECD

A number of other city-based studies have been undertaken; these are reviewed in the following paragraphs. In the first instance a collection of four studies – two from the US, two from New Zealand – are reviewed. These studies are distinctive in their emphasis on quantitative analysis. The studies undertaken in the US are for Boston (Kirshen et al (2004)) and Los Angeles (extracted from a California-state wide study,(Hayhoe et al (2004) and the update by Cayan et al (2006)), whilst in New Zealand the studies are for Hamilton (Ruth et. al. (2007) and Wellington (Jollands et. al. 2006). The studies are summarised in Table 5 below.

Table 5**. Summary of key findings from scoping studies**

Study	Study method overview	Key study results
Boston (Kirshen et al (2004)) Climate's Long-term Impacts on Metro Boston (CLIMB)	<u>Impacts</u> Focuses on transportation, water resources, coastal and riverine flooding, energy and health. Stakeholder engagement. Dynamic analytical modelling tool used, with a GIS incorporating socio-economic change. Two GCM climate scenarios and various sensitivity analyses used <u>Adaptation</u> Cost-effectiveness analysis	SLR 0.61 metres to 2100 1 in 100-year storm → 1 in 10-year storm; 1 in 500-year storm → 100-year storm. Coastal flooding: CC-induced cost - property damage + emergency services, up to USD94 billion to 2100. Days above 90∞F per year – 15 to 30 by 2050. Water supply shortfalls – need supplementary supplies Failure to take any adaptation action is most ineffective and expensive response; Early actions result in less total adaptation and impact costs; Precautionary approaches using softer measures generally more cost-effective e.g. integrating water quality management to include land use, drainage, and waste water treatment
Los Angeles (Hayhoe et. al. (2004))	Desk based study: quantified impacts in California (Los Angeles, Sacramento, Fresno, and Shasta Dam) from two climate models and two scenarios	B1 scenario: heat-waves 4X ↑ freq.; heat-related mortality 2-3X ↑ freq.; alpine/subalpine forests 50–75% ↓; Sierra snow-pack ↓30–70%. A1f1 scenario: heat-waves waves 6-8X ↑ freq.; heat-related mortality 5-7X ↑ freq.; alpine/subalpine forests 75-90% ↓; Sierra snow-pack ↓73–90%. Disruption of water supply
Hamilton (Ruth et. al. (2007)	Part of Climate's Long-term Impacts on New Zealand Infrastructure (CLINZI). Low and high emissions scenarios from down-scaled CSIRO and Hadley models, to 2030. Combine popn. projections with climate scenarios (using climate variable means only) to predict water demand	40% chance of water shortages in any given year after 2030. Results largely driven by changes in popn.; not significantly affected by changes in climate (though' no extremes). Identified sectoral interactions between e.g. water and health etc.
Wellington (Jollands et. al. 2006)	Part of CLINZI. Used results from 6 GCMs, downscaled for 2030. Climate variable means and extremes	SLR by about 0.2 m by 2050 and 0.5 m by 2100. Only very slightly increased p.c. water demand due to CC; increase dominated by popn. growth. Limited CC impacts on transport, electricity demand and health.

The four studies all use quantitative climate scenario data to make quantitative estimates of impacts, and in all four studies these estimates are principally derived with respect to water resources, again reflecting current concerns in the cities' patterns of socio-economic development. In this regard, the two studies undertaken in New Zealand clearly elucidate the fact that socio-economic pressures in the medium-term at least are likely to dominate pressures resulting from climate change. The CLIMB study for Boston is unique for undertaking an initial cost-effectiveness analysis of adaptation options, comparing "hard" defence-based options with "soft" accommodating, pre-emptive approaches – the latter largely comprising no-regret options and therefore being evaluated as more cost-effective. This study is therefore exceptional in considering adaptation costs.

3.2.2 Other city studies: Non-OECD

Whilst there are studies with detailed regional climate predictions for India (Kumar et al, 2006) and emerging detailed sectoral studies in India and China[23], for other areas of the world city-based impact studies are borne out of a perception that specific geographical features make large population centres particularly vulnerable to climate change impacts. For example, Sherbinin et. al. (2006) examines the vulnerabilities of Mumbai, Rio de Janeiro and Shanghai – coastal megacities. They use the Canadian Climate Centre's B2 and A2 scenarios and project sea level rise of 50cm by 2050 for all three cities and temperature and precipitation quarterly mean changes also for 2050. They then undertake qualitative vulnerability assessments combining system characteristics and climate and socio-economic stresses.

Sherbinin et. al. find the following: In Mumbai the projected A2 precipitation fall exacerbates the city's water supply shortfall and so likely to lead to more seasonal in-migrations. In considering sea-level rise they quote TERI (1996) that shows that a 1-metre rise results in USD71bn damages without dykes, reduced to USD33bn with dykes. A 50cm rise in sea-level rise renders squatter communities uninhabitable; there is also structural instability of buildings on landfill as a result of coastal shifting. Adaptation possibilities currently consist of shifting the old city to adjacent suburbs or to Navi Mumbai. They point out that there are weaknesses in adaptive capacity in an institutional sense; there is a Disaster Management Plan but no proactive measures are being taken at present. The best hope for such measures is thought to reside in informal institutions such as the national slum dwellers federation, plus overseas support (from e.g. diaspora).

In Rio de Janeiro, principal impacts identified include drinking water scarcity and electricity shortages; flooding from intense precipitation and ENSO events; coastal erosion demanding increased nourishment costs and a potential tourism impact; a reduced capacity for wetlands to act as buffer against storm surges; algae blooms, and landslides. Like Mumbai there is an organisation responsible for disaster management - Civil Defence - which incorporates the emergency services but undertakes no pre-emptive disaster preparation. Possible other adaptation measures include new zoning to restrict building in hazard prone areas. Beach nourishment is on-going but no dykes are planned.

In Shanghai, Sherbinin et. al. find that sea-level rise is projected to be exacerbated by subsidence whilst there is a threat of flooding from the Xangtse river. Building vulnerability is greatest from the shifting ground and the threat of coastal erosion. Current disaster management centres on the provision of volunteer civil defence networks, though in the future, afforestation and reforestation is highlighted as being a possible effective measure, along with dyke construction.

A number of other studies in developing countries focus primarily on sea-level rise, reflecting the fact that the cities they consider are at low-lying coastal elevations with limited adaptive capacity. Dossou and Glehouenou-Dossou (2007) identify the impact on the city of Cotonour in Benin of a rise in sea level. They use the MAGICC IPCC scenario IS92a to construct "Average", "extreme" and "basic" sea level

[23] As examples the UK Defra programmes on Investigating the impacts of Climate Change in India, and impacts on agriculture in China.

scenarios. They anticipate resulting coastal erosion, flooding and salt penetration of water table. Additionally, they project threats to road infrastructure & residential districts, industrial & tourism sectors, ecosystem damage and threats to fishing communities. There is an adaptation plan being developed which currently consists of two options (awaiting funding). One option is to introduce groynes (rigid hydraulic structure built out from the shore) which effectively transfer erosion along coast, away from the city, in tandem with an offer of compensation to those adversely affected. The alternative is to move infrastructure, for example building a new airport on higher ground.

Ng and Mendelsohn (2005) examines three sea level rise scenarios to 2100 for Singapore, and investigates whether the city should defend the coast or allow it to be inundated. study estimates the area of inundated land from these and values using (sampled) land use values. These are compared against the cost of protection. The study found that, across ten coastal sites representing all market land in Singapore, protection was the lowest cost strategy. The annual cost of protecting the coasts of Singapore will rise over time as the sea level rises and will range from 0.3 to 5.7 million USD by 2050 to 0.9 to 16.8 million USD by 2100. The present value of these costs ranges from 0.17 to 3.08 million USD depending on the sea level rise scenario.

Finally, Alam and Golam Rabbani (2007) undertake a scoping of vulnerabilities and responses to climate change for Dhaka. Focusing on impacts caused by sea level and riverine flooding/drainage congestion and heat stress, exacerbated by urban heat island, they note the costs of the 1998 riverine flooding, combined with high tide, being USD47m to building infrastructure. Additionally, there were industry losses totalling USD66m, waste & sewerage costs of USD9m; and costs to combined utilities of USD20m. There were also 284 deaths and 190,000 hospital admissions. Previous floods in 1988 had stimulated a flood protection plan which was initiated and undertaken and in fact helped to protect 50% of city in 1998. However, existing plans remain stalled and do not account for climate change.

The range of non-OECD city-level studies principally, though not solely, investigate the flood risks arising from sea-level rise. They are all alert to the context-specific factors that influence the range of adaptation responses. However, the Ng and Mendelsohn study differentiates itself from the other studies by considering the cost-effectiveness of adaptation options.

3.2.3 Summary

From this review of city-scale climate impact studies, some conclusions emerge:

- The analysis of impacts at a city-scale level is at a very early stage. There are very few detailed studies and these studies are largely qualitative in nature. Frequently, quantitative climate scenarios are used but interpreted within a qualitative assessment of impacts. Quantification in order to guide decision-making is even rarer – the cost-effectiveness analysis undertaken in the study of Boston, (Kirshen et. al. 2004), being an exception.

- There is a dominance of evidence from developed countries and a scarcity from developing countries. Nonetheless, it is likely, (Huq et. al. (2007), that due to the higher vulnerabilities within developing country cities, impacts will be more important in these cities[24]. Specifically, this is because many of the largest changes are projected to occur in these countries; their economies rely more on climate-sensitive activities; many operate close to environmental and climatic tolerance levels; and their ability to adapt may be limited because of technical, economic and institutional limitations (Tol et al, 2004). These countries are also where future growth of population and urbanisation levels are likely to

[24] This may not be equally true of economic costs, due to the high concentration of economic assets in the OECD.

be highest. The effects are likely to be greatest for the poorest within these countries, and they potentially exacerbate inequities in health status and access to adequate food, clean water, and other resources (Sanderson, 2000).

- There is clearly a strong variability with location such that vulnerability and impacts on cities will be site-specific (Sherbinin et. al., 2007). The impacts depend upon the urban geography and the physical location of the city in question.

- Vulnerability to climate change will depend on changes in climate variability in the form of extreme events (e.g. storm surge and floods, droughts, fire, extreme temperature) but also changes in climatic means (e.g. sea-level rise (coastal erosion) and temperature (energy demand)).

- The priority given to coastal cities and also to extremes in the 4th Assessment Report is a reflection of the literature available, rather than (necessarily) the results of detailed cross-sectoral assessments. Indications from some of the city studies show additional areas e.g. urban heat island impacts, might be as important in economic terms.

- Historical analogues of extreme events and their costs are sometimes used to imply the scale of costs potentially involved but they are not generally related to forward-projecting climate change scenarios.

- Most of the studies are not explicit in determining the potential impact of socio-economic change on the size of the impacts, i.e. analysis is presented as the sum of the socio-economic and climate signals. Whilst this is interesting in showing total changes (and in formulating adaptation responses), it may be unhelpful in respect of policy appraisal that wishes to weigh mitigation efforts against adaptation efforts.

- Even when there are similar impacts covered, the methodological approach varies e.g. there is no consistency in the use of climate models and scenarios or mean or extreme parameters. It is therefore not possible to compare quantitative results between studies. This is expanded further in the next section on specific impacts.

4. Methodology Review

In order to highlight the extent of coverage of the city-scale impact studies reviewed above, we frame the studies in terms of the risk matrix developed by Downing and Watkiss (Downing and Watkiss, 2003; Watkiss et al, 2006 – reported in Fig 20.4 of WGII).

The studies were compared for their coverage against this risk matrix (Figure 1), in relation to

1. The uncertainty of climate change impacts, covering:

- Impacts that can be predicted with relative confidence and where the confidence in the direction of effect is certain (e.g. average temperature);

- Impacts where prediction is more uncertain, and where models often give different levels of impacts, or even predictions of a different sign (positive/negative), as with for example regional estimates of levels of precipitation, or frequency or magnitude of extreme events;

- Impacts where prediction is highly uncertain, notably around the major 'tipping points' commonly identified (major climate discontinuities or irreversibilities, such as the West Antarctic ice sheet, methane hydrates, etc, as in (Schellnhuber et al 2005).

2. The uncertainty in type of sectors, covering:

- Market sectors (e.g. estimates captured through markets such as energy and agriculture);

- Non-market sectors (e.g. estimates for health and ecosystems which rely on other economic approaches, as advanced through the environmental economics literature);

- A third category of non-market effects – labelled socially contingent effects – defined as large scale dynamics related to human values and equity that are very poorly represented in damage estimates based on marginal cost values, e.g. regional conflict, famine, poverty.

Figure 2. **Coverage of city studies against the risk matrix**

	Market	**Non -Market**	**Socially contingent**
Projection **e.g. mean temperature or SLR**	**SLR** - Singapore (V) - Mumbai (V) - Alexandria (V) **Energy** - Athens (Q) - Boston (Q) - California (Q)	**SLR non-market** - Singapore (V) **Health** - Lisbon (Q) - Melbourne, Sydney (Q) - Boston (Q) - Toronto (Q) - Los Angeles (Q)	**SLR Migration** - Nile delta (qualit.)
Bounded **e.g. precipitation and extremes**	**SLR and storm** - New York (V) - Boston (V) - London (Q) **Riverine flooding** - Boston (V) **Transport / infrastructure** - Boston (Q) - Wellington	**Water** - Los Angeles (semi-Q)) - London (semi-Q)	None
Major change **e.g. major tipping points**	**Major SLR** - London 4 to 5 m SLR	None	None

Key: (Q) Quantified, i.e. expressed in physical terms; (V) Valued i.e. expressed in monetary terms.

Most studies are constrained to market sectors, primarily sea level rise – though some of these include extremes (e.g. storm surge) as well as mean sea level rise. A few studies cover non-market damages, particularly health, though do not have valuation. Some locally-specific precipitation effects (riverine flooding) are considered. Almost none cover socially contingent effects and major/catastrophic events.

The broad state-of-the-art in city based assessments of impacts and economic costs is therefore at an early stage. These mirror a more general trend on impact and cost studies. Part of the reason for this is due to the complex methodological issues involved in undertaking such studies. The issues have been explored in recent review work, notably by the EEA (EEA, 2007b). This found:

- Understanding and improving methodological issues, and the way they can affect the economic costs, is essential to ensure that the information generated can be effectively used in Regional and national policy developments (and by implication here cities).

- The review shows that the definitions of the economic costs of climate change and the costs of adaptation vary significantly, and involve complex concepts that are often dealt with differently by studies.

- The evidence provided shows that the understanding of these economic costs is still incomplete and permeated by uncertainty. Different assumptions and choices in the methodology for cost assessment lead to a very wide range of estimates of costs of climate change (and the costs and benefits of adaptation).

This review also found a number of challenges which should be addressed to improve the information on the economic costs of climate change. These include (EEA, 2007b):

- Despite recent progress, a major difficulty remains the incomplete understanding of climate change itself, in particular the regional effects of climate change, and specifically the coverage across the range of different climate change effects.

- Current scenarios and impact studies use relatively crude spatial and temporal resolutions. Despite a growing number of country-level case studies, the current knowledge of impacts is still incomplete and does not allow for a careful, detailed comparison across regions.

- Differences in assumptions often make it difficult to compare studies. Only a few studies provide a consistent picture, based on a uniform assumptions on climate, socio-economics, etc. and many studies extrapolate between regions. There is a need for consistent studies.

- Non-market damages, indirect effects, horizontal inter-linkages, and the socio-political implications of climate change are still poorly understood. There is a particular gap on the analysis of economic costs and benefits of biodiversity. Analysis of uncertainties, transient effects, and the influence of climate variability are other factors deserving more attention. There is a need to move towards dynamic assessment, for impacts and valuation.

- Major advances are needed to understand the economics of adaptation. Adaptation will entail complex behavioural, technological and institutional adjustments at all levels of society, and not all population groups will be equally capable of adapting. Such analysis is complicated by the strong link between adaptation and socio-economic scenarios/development. Further work is needed to progress the costs and benefits of adaptation, and the consideration of maladaptation.

- There is a need to progress the policy aspects (and the policy process) in relation to the costs of inaction and the costs and benefits of adaptation.

- These also apply to the issue of adaptation, though there are also additional issues with the type of adaptation (autonomous or planned), the level and timing of adaptation (e.g.

anticipatory or reactive), the types of costs of adaptation (including direct costs and transition costs), the ancillary benefits of adaptation and the distributional aspects of adaptation.

Moving to the city level, we add the following aspects:

- The analysis of impacts is further complicated by the data resolution of climate models and issues of down-scaling. This is a particular issue in relation to extremes, which are important in determining impacts at the city scale. The issues are further compounded by local micro-climates and particularly heat island effects.

- At the city scale, there seems to be less consideration of socio-economic scenarios. This should potentially include consideration of demographic and economic growth, technological changes, and even lifestyle and governance factors. Most studies have fairly narrowly defined socio-economic scenarios (population growth). Moreover, many studies are rarely explicit whether the impacts relate to the combined socio-economic and climate scenarios, or the climate induced change only (though there are some exceptions). While the combined effect is important in determining the adaptation response, it is misleading in respect of policy analysis and the analysis of policy intervention.

- The economics of adaptation (costs and benefits) are at an early stage, and most studies do not attempt to quantify (nor value) adaptation (nor importantly residual damage after adaptation). In too many cases, adaptation is described in terms of climate proofing, with no regard to the cost-effectiveness of action, the actual reductions in economic costs that adaptation will achieve, or the residual economic impacts after adaptation (and consideration of benefits and costs). While this can be explained by the early stages, and the need to raise awareness and build capacity to the impacts of climate change and the need for adaptation, it holds a major potential risk that cities will embark on adaptation strategies that are inefficient. Alongside the urgent need to consider the economics of adaptation, further work into maladaptation is highlighted as a priority.

A number of recommendations are made with respect to the rest of this programme of work.

- First, it seems sensible to progress the analysis of coastal flooding, as this is highlighted by many studies as the primary concern.

- Second, the analysis of extremes, is a priority, including both direct and indirect effects.

- Third, there is a need to broaden the analysis from these two impacts. It is highlighted that consideration of energy could be extremely important as a) it is associated with mean rather than extreme changes and so there is a high confidence in the likelihood of effects and b) it dominates existing IAM results for the economics of climate change and is therefore likely to be a priority for cities as well.

- Finally, there is a need to bring an economic perspective to the consideration of adaptation.

5. Conclusions and research recommendations

This paper presents an overview of the emerging literature relating to climate change impacts on cities, and treatment of adaptation. The focus of the review has been on assessing the extent to which quantitative and monetary measures of impacts and adaptation have been developed in order to aid cost-effective and cost-efficient responses at the city scale. In this final section we draw together a number of conclusions relevant to climate change policy and also to future research needs.

The study of potential climate change impacts and responses to them is a relatively new phenomenon at the scale of the city but fit within a general trend within climate impact assessment towards more local scale analysis. This trend is, in part, due to the growing sophistication of climate modelling that now allows for increasingly robust ways in which to down-scale climate change scenarios. It is, perhaps, also reflective of the fact that climate change policy is increasingly recognising the need to address the unavoidable consequences of climate change as well as reducing greenhouse gas emissions.

Within the last decade, a number of OECD country cities have undertaken multi-sectoral analysis of potential climate change impacts. Foremost amongst these – in terms of sophistication - are the studies for London, New York, Boston, Hamilton and Wellington. These studies tend to use down-scaled climate change scenarios over 30-100 year time-spans to identify and describe potential impacts. Impact descriptions are primarily qualitative, though some quantitative analysis is undertaken that combines socio-economic trends e.g. in population with established climate variable – impact relationships derived from historical time-series data. Estimates of the costs of historical extreme weather events are then extrapolated and summed under changing event frequencies derived from the climate scenarios. In the majority of these studies, climate change impacts are identified as being potentially significant factors to consider in making medium-to-long term decisions relating to development patterns within the cities. Geographical coverage of studies is, however, low to date, for example, almost no inland cities have undertaken impact analysis.

The dominant impacts from these and similar studies – in terms of coverage – are those related to flooding (from sea level rise and rivers), water resource availability, public health from heat extremes and ozone, and energy demand. Emphasis on these impact categories reflects areas where public infrastructure is currently under most pressure from socio-economic development, as well as where a city's resource needs are most climate-sensitive. Given the relatively resource-intensive nature of climate impact analysis it seems sensible for future city-scale research to be prioritised in a similar way. It seems clear from these studies that the prioritisation process benefits from stakeholder engagement at an early stage. Development of institutional responsibilities for co-ordinating such research at the outset has also seen to be effective; institutional and wider stakeholder buy-in also seems critical in creating momentum and obtaining resources for subsequent in-depth analysis of sectoral impacts and adaptation needs.

The focus of studies in non-OECD country cities has almost exclusively been on increased flood risks from sea-level rise, reflecting the fact that that the majority of large non-OECD cities are sited in coastal locations. This, coupled with the fact that climate change impact analysis is relatively advanced for sea-level rise, has ensured that limited resources available for climate research in these countries has been focused on this single impact. However, whilst the sea-level rise has frequently been expressed in terms of centimetre increase by a certain year, this has generally not been translated into quantitative estimates of the physical impacts in individual cities. This, in tandem with the fact that institutional capacity and buy-in is often limited in these cities, means that climate change impact analysis at the city-scale in these countries is not as advanced as it is in some OECD countries. This conclusion should, however, be considered in the context that the IPCC suggests that climate change impacts will be more severe in developing countries.

In general, however, city-scale analysis is sparse, and quantification in physical or monetary terms, is rare. This suggests that it is only now being recognised that effective adaptation to climate change impacts requires the use of institutional structures, e.g. local authorities and their administrations, water companies etc., that exist at the city-scale. It also suggests that there is low recognition of the fact that many of the most acute, direct impacts of climate change e.g. the health impacts of the Urban Heat Island effect, SLR-induced coastal flooding, limits to water availability etc will be felt by the large numbers of high-density living populations that comprise a city. The city-scale studies reviewed above are in many ways exceptions to this conclusion; in this sense they should therefore be seen as templates for city-scale analysis.

Many of the other conclusions that can be drawn from a review of city-scale studies are equally applicable to climate impact analysis more generally. These include: the limited analysis of climatic extremes; the limited coverage of impacts; the limited quantification of impact risks and subsequent use in decision-informing tools (e.g. cost-effectiveness analysis or cost-benefit analysis); the limited use of socio-economic scenarios in impact analysis, and; the varying but principally low level of recognition of cross-sectoral linkages between impacts. Future city-scale studies would therefore benefit from considering wider developments in the impact literature. At the same time, adaptation options are increasingly well-known and option identification appears to be running ahead of the ability to evaluate the alternatives within an adaptation strategy.

As highlighted earlier, the existing studies are useful for a city authority to consider before embarking on its own city-specific study. However, one clear message that emerges from the studies is that their results are not readily transferable to other locations. The Sherbinin study of the three studies is a good illustration of the fact that geographical differences have significant effects on local climates. Despite recent progress a major difficulty remains the incomplete understanding of climate change itself, in particular the regional effects of climate change and specifically the coverage across the range of different climate change effects. These problems are amplified at the city scale, where the analysis of impacts is further complicated by the data resolution of climate models and issues of down-scaling. This is a particular issue in relation to extremes, which are important in determining impacts at the city scale. The issues are further compounded by local micro-climates and particularly heat island effects. Climatic down-scaling low-cost applications are therefore a priority in future research.

Following on from this last point, the evolution of common impact methodologies is a research priority since it will enable a greater degree of comparison and transferability of results between cities and – in the instance where public funds for adaptation are distributed at a global scale – resources can more efficiently be allocated when relative vulnerabilities can be compared.

The research recommendations emerging from this study can be summarised in the following bullet points.

- The need to improve the model disaggregation to allow analysis at the city level (and likewise to allow improved aggregation up for wider assessment);
- Related to this, the need for consistency in scenario analysis and methods, as well as variation and uncertainty;
- The need to increase the number of real case studies;
- The need to investigate the rates and speeds of climate change and how these affect impacts and adaptation;
- The need to strengthen the degree of integration and completeness of existing analysis, and to ensure consistency;
- The need to expand the coverage of studies, to include non-market damages and indirect costs, and the impacts of extreme events and potentially major catastrophic events;

- The need to investigate "realistic" adaptation options by different stakeholders in different socio-economic, cultural and political settings and identify adaptation options (e.g. good practice);
- The need to progress analysis of the costs of adaptation, and to consider an economic perspective.

Specific immediate priorities for this programme include the consideration of sea level rise on major cities and economic costs (including indirect effects) of extremes. The scope of analysis could usefully also be widened to include analysis on energy demand (e.g. in case studies), and further methodological work on impact/economic assessment and especially adaptation.

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