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Climate Change Impacts and Adaptation in Cities: A Review of the Literature

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Abstract Many of the decisions relating to future urban development require information on climate change risks to cities This review of the academic and "grey" literature provides an overview assessment of the state of the art in the quantification and valuation of climate risks at the city-scale. We find that whilst a small number of cities, mostly in OECD countries, have derived quantitative estimates of the costs of climate change risks under alternative scenarios, this form of analysis is in its infancy. The climate risks most frequently addressed in existing studies are associated with sea-level rise, health and water resources. Other sectors such as energy, transport, and built infrastructure remain less studied. The review has also undertaken a case study to examine the progress in two cities – London and New York – which are relatively advanced in the assessment of climate risks and adaptation. The case studies show that these cities have benefited from stakeholder engagement at an early stage in their risk assessments. They have also benefited from the development of specific institutional responsibilities for co-ordinating such research from the outset. This involvement has been critical in creating momentum and obtaining resources for subsequent in-depth analysis of sectoral impacts and adaptation needs..While low cost climate down-scaling applications would be useful in future research, the greatest priority is to develop responses that can work within the high future uncertainty of future climate change, to build resilience and maintain flexibility. This can best be used within the context of established risk management practices.

Keywords: urban environment; climate risk assessment; adaptation; economic costs; cost-benefit analysis.

1. Introduction

Warming of the climate system is unequivocal, as outlined in the recent IPCC 4th Assessment Report (WG I technical summary, Solomon et al, 2007) and without significant changes in policy, the trend in global emissions of greenhouse gases and associated 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 and the proportion is set to rise further in future years (UN, 2006). 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 for mitigation action (e.g. within the C40 Large Cities Climate Leadership Group). Attention is now also turning to consideration of the impacts on cities of climate change itself. A principal benefit of grounding global climate change at the local scale is that it may make the associated risks, or opportunities, more relevant to many private and public agents who are charged with designing and implementing possible responses. For example, analysis at the city scale is likely to coincide more closely with local administrative boundaries and so facilitate decisions related to adaptation at an appropriate level of governance.

These advantages of city-scale assessments are likely to be strengthened as a number of potentially significant climate change impacts are either unique to urban areas or exacerbated in urban areas (Lindley et. al. (2006)). For example, "surface sealing" that inhibits rainwater percolation leads to stress on urban drainage systems. Other urban-specific infrastructures, such as underground transport systems, may also have particular vulnerabilities related to extreme events, with uniquely fashioned adaptation responses. Further, flood events are examples of impacts that are potentially more severe in urban areas simply because of the relatively high density of population.

However, whilst these specific characteristics argue strongly for city-scale assessments, it is important that other spatially-defined determinants are considered. For example, a given impact within a city may have differential consequences depending on the relative vulnerabilities of people, ecosystems and infrastructure, etc. across the city and accordingly, the form of adaptation may also differ. It is also important to highlight the interdependencies that exist between the inhabitants of the city, its immediate hinterland, and the wider, global, economic and social context. Thus, for example, cities such as London or New York are reliant on food imported from surrounding rural areas, national production and even from other countries. Similarly, transport links may support both daily commuter flows from surrounding areas as well as inter-continental movements of personnel and goods. Therefore, climate change impacts on agricultural production or transport infrastructure will have knock-on effects on city populations, just as effects on cities will have knock-on effects that extend far beyond municipal borders.

The IPCC also notes that many adaptive measures, (e.g. cooling in buildings), associated with cities' built environment have consequences for mitigation strategies. However, whilst 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, be they mitigation or adaptation-based.

This review paper summarises the evidence base relating to climate change impacts and adaptation at the city scale, with a focus on whether this has been expressed in quantitative terms. It also reviews how this information has been used, for example: as a metric with which to communicate the possible severity of climate change impacts; as an input to the application of decision-support tools (such as cost-benefit, or cost-effectiveness analysis); or to help evaluation potential adaptation options and strategies. Here, we are primarily interested in major world cities though many of the findings of this literature review have relevance to smaller cities.

A variety of potential impacts (and potential benefits) of climate change on cities have been identified to date. A number of recent reviews have described these, including the IPCC Third and Fourth Assessment Reports (Scott et al, 2001, and Wilbanks et. al. 2007, respectively); Bigio, 2003; McEvoy, 2007; Wilby, 2007; and Huq et al, 2007. Their consensus findings are that the most important effects of climate change on cities are likely to be:

- Effects of sea level rise on coastal cities (including the effects of storm surges);

- Effects of extreme events on built infrastructure (e.g. from wind storms and storm surges, floods from heavy precipitation events, heat extremes and droughts);
- Effects on health (from heat and cold related mortality and morbidity, 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.

Less important direct impacts are thought to include those on tourism and cultural heritage, urban biodiversity and the ancillary effects of air pollution. Whilst they are not the focus of this review, there is also a set of secondary effects on cities related to the concentration of economic activity in cities and their inter-dependencies with surrounding regions. These issues include the 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 and wider economic performance, and employment patterns in the sub-region and beyond.

The majority of studies undertaken to date are 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 (LCCP, 2002; 2006; Rosenzweig and Soleck et al, 2001; 2006; NYCDEP (2008), Kirkshen et al, 2006). These studies include quantitative estimates of potential impacts, in physical and/or monetary terms, as well as some consideration of adaptation options. The scope of impact coverage is, however, partial. Other city-scale impact studies that address, in qualitative terms, a small number of potentially important climate change impacts are focussed on cities in Canada (e.g. Toronto, Montreal, Vancouver – see e.g. Ligeti, (2007)) and Australia and New Zealand (e.g. Sydney, Melbourne, Wellington – see Preston and Jones, (2006), Maunsell, 2008), as well as sea level rise studies in Alexandria and Singapore (OECD, 2004; Ng and Mendelsohn, 2005). A larger number of cities in different world regions have undertaken some partial analysis or assessment of likely climate change impacts.

Whilst there is a wide coverage of locations across continents, see Figure 1, most studies have focused on coastal cities, where a relatively certain climate change impact – sea-level rise – is coupled with a general trend of population growth. There is much less information relating to inland cities. Consequently, there is a significant evidence gap on the impacts of climate change across the full range of geographical locations and impact categories, including energy demand, water resources and riverine flooding that might be thought to be significant. The evidence that exists shows a strong variation in impacts with location and site. The current literature is therefore likely to be indicative, only, of the true scope and extent of climate change in cities.

The review also considers differences in methodological approaches, particularly relating to quantification and monetisation of city-scale climate change impacts and adaptation. The approaches used to generate quantitative information are found to differ substantially and lack consistency with each other. Consequently, several areas are highlighted to improve methods and encourage consistency between studies, including the treatment of climate modelling, socio-economic scenarios and monetary valuation of market and non-market impacts, where comparability in approaches may serve to more easily facilitate useful transfer of findings between cities.

Nevertheless, and despite the limitations in coverage and methods, some conclusions relevant to policy processes can be drawn. First, city-scale vulnerabilities are likely to be greater in developing country cities, primarily reflecting the fact that the population of these cities is often growing faster than their physical infrastructure capacity, and that their existing adaptation deficit to current climate variability as well as future exposure to climate change is greater than in developed countries. Most adaptive action to date has focused on awareness-raising, though progress in mega-cities such as London and New York suggests that climate change impacts can also be more formally incorporated into current planning and decision-making as long as there exists the institutional structure and co-ordination capacity. The existing mega-city 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.

We therefore suggest in the conclusions to this paper that with limited resources, future research effort might focus on a number of scoping case studies using common methods – possibly on a global pooled funding basis - that allow other cities to explore the potential for transfer of results between cities with similar location or vulnerability characteristics. Subsequent studies may be then taken 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. Clearly, whilst sea level rise and extreme weather events 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 prioritised physical impacts, to a quantified analysis of the monetary damages. The issue of energy demand (particularly in existing 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, together with a large number of associated cross-sectoral impacts that may be identified from taking a spatially-defined assessment such as this.

We also highlight the need to think about future research in the context of overall objectives and subsequent action. The quantification and valuation of large future risks is a key step to raising awareness and can help identify possible priorities. However, such studies maybe of less relevance in designing immediate adaptation responses where uncertainty dictates that qualitative approaches are more appropriate since they may be less likely to mislead (Füssel and Klein, 2006). Accordingly, there is also a need to consider how city scale research can help inform early priorities where action is economically rational, including building capacity, addressing current climate variability and focusing on no regret measures, as well as investigating early decisions which involve longer-term considerations such as with infrastructure and spatial planning, but where – in all cases – the context is of continued profound uncertainty as to the nature and timing of climatic change (Watkiss et al, 2009).

Section 2 of this review provides a sectoral-based overview of the effects of climate change on cities. Section 3 then reviews the literature on climate impact assessments relating to a small number of individual cities where such assessments have begun to be used in decision-making relating to climate change adaptation. Finally, Section 4 draws together conclusions relating to methodological issues and the future policy use of city-scale studies and identifies principal research gaps.

This review focuses specifically on cities, and explores the extent to which economic analysis has been incorporated into the climate change impacts at this scale, as well as the potential 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 towards the economic consideration of adaptation, and what are the limitations to such analysis.

2. The Impacts of Climate Change on Cities: an overview

The two most recent IPCC reports, in 2001 and 2007 draw conclusions on the effects of climate change from a city-scale perspective. The 2001 chapter on Human Settlements, Energy and Industry, (Scott et. al. 2001), concluded that:

"Climate change is more likely to have important impacts on the development of settlements in resource-dependent regions or coastal or riverine locations. 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 report also concluded that the vulnerability of settlements was mainly due to three factors: location, with coastal and riverine flooding providing the dominant risk; economy, with those areas that are dependent on weather-related sectors at most risk, and; size, with larger settlements bearing a greater aggregate risk, though perhaps also having greater adaptive capacity (resources) to limit risks.

The 2007 chapter on Industry, Settlements and Society, (Wilbanks, et al 2007), reinforces these earlier findings, though places climate change impacts more directly in the context of socio-economic change and more explicitly recognises the potential for adaptation. The summary report 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.….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'*

The report also concludes that poor communities can be especially vulnerable, in particular those concentrated in high-risk areas, since 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 seen as often being capable of considerable adaptation, depending heavily on the competence and capacity of individuals, communities, enterprises and local governments, and on the access to financial and other resources. These conclusions are drawn with "very high confidence" by the IPCC.

In contrast to the broader perspective adopted by the IPCC, our review 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. A number of generic methodological issues with these objectives are highlighted at this point in order to provide orientation in the subsequent discussion of the city-scale literature.

EEA (2007) highlights key methodological components relating to the quantification and valuation of climate change impacts at the global and regional sale. These include: treatment of scenarios (both climate and socio-economic projections); issues of valuation (market and non-market effects; indirect effects on the economy); approaches taken to spatial and temporal variation; uncertainty and irreversibility (especially in relation to large-scale irreversible events); and coverage (which climate parameters, and which impact categories, are included).

A clear example of the need to consider these aspects in quantitative city level analysis arises from the treatment of 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), need to be explored in city-scale assessments, 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, 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, and very different levels of change in the frequency or intensity of extreme events, such as those relating to flood risk, wind-storms and heat 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-scale studies to date have interpreted larger- geographical 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.

Our review draws upon empirical studies from both the academic and "grey" literature. This literature may be further disaggregated to include: a) city studies/city analogue studies commissioned e.g. by city-level public authorities; b) country-scale studies commissioned e.g. by national environment ministries; c) sectoral-based studies focussed on (sub-) sectors of interest e.g. insurance, commissioned by sectoral representative bodies; d) extreme event studies i.e. commissioned following an exceptional weather event e.g. Summer 2003 heat-wave in Europe, but that have some focus on cities, and e) academic journals i.e. peer-reviewed versions of studies in a-d, above.

Our 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[1]. We build on Wilbanks et. al. and review the following studies of major global cities, listed in the Table 1, below[2]. This is a rapidly evolving area and we acknowledge additional studies are emerging. It is also highlighted that a much wider group of cities have published climate change action plans (see C40, 2010), but these are primarily focused on mitigation, which is not the focus of this paper.

Table 1. Selection of Major City Studies considered in Current Review

City	Nature of study	Type
Europe		
Athens	Study of future air conditioning demand for electricity from climate change. (Giannakopoulous et al, 2006)	Quantitative
Helsinki	Climate change in urban planning (flooding) VTT (2008)	Quantitative
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
Paris	Analysis of 2003 heatwave on health / infrastructure (impacts and economic valuation), e.g. Gillet, 2006; economic impacts for buildings (Hallegatte et al, 2006); Paris Climate Plan (Mairie de Paris, 2007)	Historic
Stockholm	Ekeland (2007) City of Stockholm. Quantitative analysis of sea level risk, qualitative analysis of other possible impacts	Qualitative/ Quantitative
North America		
Boston	Climate's Long-term Impacts on Metro Boston. Transport, Energy, Health (all	Quantitative

[1] 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).

[2] Note there are many additional smaller city studies, e.g. Hamilton City, New Zealand (Jollands et al., 2005), Bilboa, Spain (Metroeconomica, 2006), Manchester (ASSCUE, 2007), Halifax, Canada (Murphy et al, 2006), Homer, Keene,King County in the US (Pew Centre, 2007) and regions (e.g. New Brunswick, 2006, Australian coast) that are not considered here. There are also a large number of sub-national (regional) studies that include consideration of major urban areas. This includes regional studies in the UK (for a summary of these, see West and Gawith, 2005), state studies in Australia (e.g. New South Wales, 2005; work as part of the Garnaut Review (2008)); provinces/territories in Canada (e.g. Natural Resources Canada (2004, 2007), Burton and Dore, 2000) and; state studies in the US (for a review see Pew Centre (2007: 2009) which highlights research activities in Alaska, California, Florida, Maryland, Massachusetts, New Hampshire, Oregon, and Washington in particular, though a further number of state studies are emerging with a quantitative focus).

	quantitative) and Water (valuation). (Kirshen et al, 2006).	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
Cincinnati, Chicago, St. Louis	Heat-waves and health from climate change (Ebi and al, 2007)	Quantitative
Florida (Miami)	Sea level rise, hurricane damage, energy for cooling and tourism (Stanton and Ackerman, 2007)	Quantitative Valuation
New York	Series of studies, e.g. Rosenzweig and Soleck et al, (2001; 2006); NYCDEP (2008), – quantification and valuation - see below.	All
Seattle	Climate Change and Seattle Department of Transportation (OCA, 2005). Consideration of recent events, and potential future multiple risks	Historic Qualitative
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.	Quantiative 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). Analysis of cities as part of Garnaut review (2008) including effects of CC on urban water supply in major cities and on port infrastructure (Maunsell, 2008) and heat effects (Bambrick, 2008).	Qualitative/ Quantitative Quantitative/ Valuation
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
Non-OECD		
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
Cotonour, Benin	Vulnerability to Climate Change in Cotonou: 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
Caracas, Venezuela	Cities, disasters and livelihoods. (Sanderson, 2000)	Qualitative
Western Cape/ Cape Town	Status Quo, Vulnerability and Adaptation Assessment of the Physical and Socio-Economic Effects of Climate Change in the Western Cape. (Midgley et al, 2005). Cape Town (Mukheibir and Ziervogel, 2007).	Qualitative (for urban)
Durban	eThekwini Municipality, EMEMD (2007)	Qualitative
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
Hong Kong	Consideration of future impacts, EPD/ERM (2010)	Qualitative
Kochi (Cochin), India	Possible vulnerabilities of Cochin, India, to climate change; impacts and response strategies to increase resilience (ORNL/CUSAT 2003)	Qualitative
Mombasa	Sea level rise, Awauro et al (2008).	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 these city studies are plotted on the map in Figure 1, below. It shows a wide coverage of locations across world regions. However, it is clear that most studies have focused on coastal cities and that there are very few studies of inland cities. There are also a number of areas that are less well covered, or omitted, that may be vulnerable to specific risks. These include some areas of the southern coast of the US and cities in the Caribbean, and in Japan/South East Asia where cities may be vulnerable to hurricane to tropical cyclone risk, as well as cities subject to water scarcity in southern Europe.

The majority of studies are single-issue, with sea level rise the most common focus, reflecting the fact that many major cities, and, indeed, over 50% of the world's population, are located in low lying areas and so potentially vulnerable to sea level rise (Nicholls 2004). This focus arises from a combination of perceived current vulnerability to climate variability from coastal flooding, the greater certainty which has been attached to the probability of sea level rise under future climate change scenarios compared to trends in many other climate variables or impacts, and the relatively easily understood impact metrics used in this context (e.g. area potentially at risk of flooding).

The second most common focus relates to the impacts of heat extremes, and – as with sea-level rise risks - primarily extends findings of heat stress arising from current climate variability to consider the potential impacts of future climate change. This rather restricted focus suggests that current literature should only be seen as indicative of the priorities of climate change faced by cities globally.

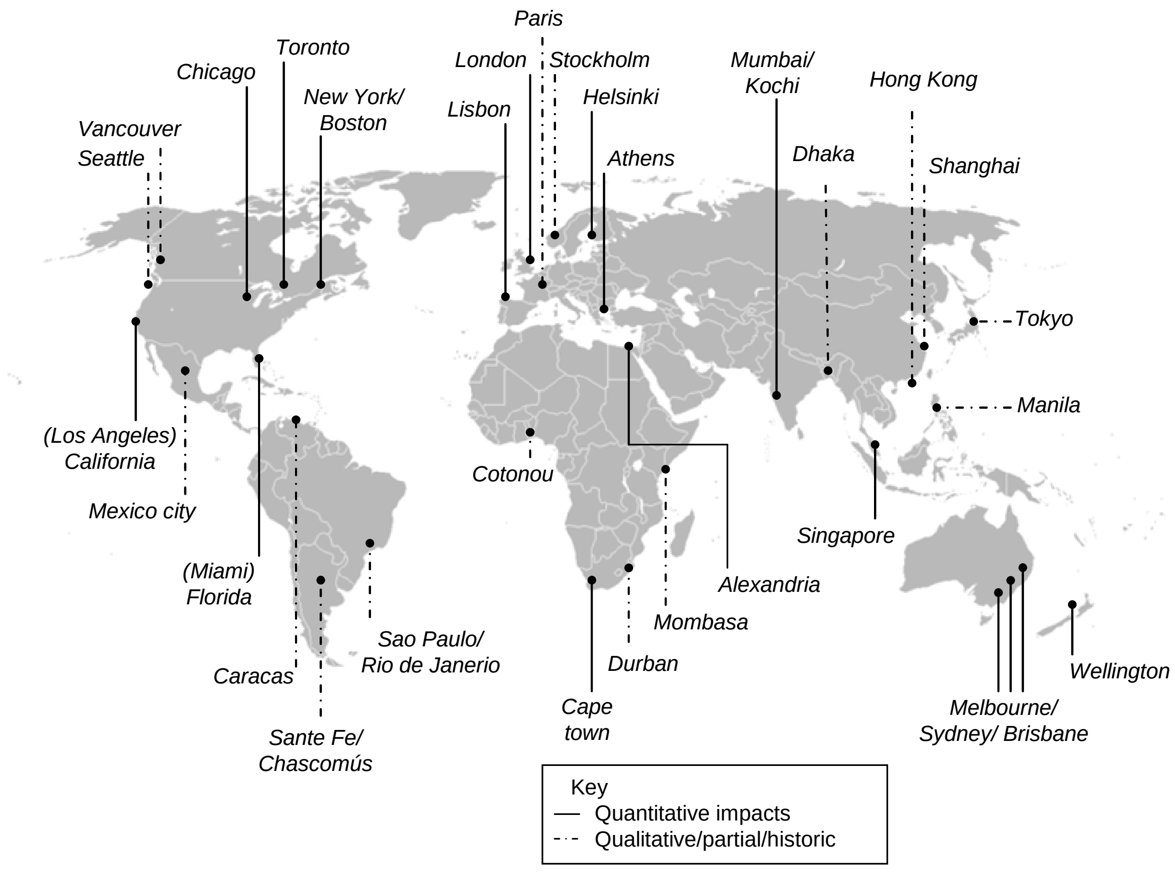


Figure 1. Geographical location of Selection of Major City Studies

The remainder of section 2 presents an overview of the city-scale impact literature within the context of the wider climate change impact literature. It is organised according to sectoral impacts, and in so doing reflects the way in which this literature has most commonly been structured to date. In part, it implicitly serves to demonstrate where there are likely to be significant city-scale impacts that are not yet recognised or reported.

Coasts

Many major cities are on low lying areas and/or close to, 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 socio-economic activities (see Nordhaus, 2006).

McGranahan et al (2006) report that larger urban settlements tend to be more concentrated in low elevation coastal zones, and that around 65% of cities with populations greater than 5 million are located in these zones. In all global regions, there are densely inhabited coastal areas and large cities that are already below normal high-tide levels, and prone to flooding from storm surges. Asian cities are found to be particularly low-lying. The most threatened coastal urban environments comprise of deltas, low-lying coastal plains, islands and barrier islands, beaches, and estuaries. Direct impacts from sea level rise include inundation and displacement, coastal erosion and land loss, 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 recreational activities.

Analysis of coastal flooding is the most advanced and well covered of all the impact categories, especially in relation to mean sea level rise, and increasingly the effects of storm surges (Nicholls et al, 2007). The increasing sophistication of geographical information systems allows detailed spatial analysis. There is a significant literature on the physical impacts and economic damages of sea level rise and coastal flooding, though much of this work has been reported at global or 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 DINAS-COAST Consortium, 2006; Hinkel and Klein, 2007; Nicholls et al., 2007a; Vafeidis et al., 2004; 2007). Despite some difficulties in estimation, there is an extensive literature reporting the direct cost of adaptation to sea level rise and estimation of the economically optimal levels of protection at a regional level (e.g. Tol, 2004; Anthoff et al., 2006; Richards and Nicholls, 2007, Yohe et al, 2006). A recent study, (Dawson et. al. (2009), assesses the costs and benefits of different combinations of adapting to the joint risks associated with coastal erosion and coastal flooding at a local level within the UK. They are able to identify the trade-offs between allowing coastal erosion without cliff protection, resulting in greater natural flood protection, and preventing coastal erosion through protection, at the expense of an increased flood risk. Cost-benefit analysis found that it would be economically efficient to adapt to the flood risk rather than to coastal erosion. At a city level, Kirshen et al (2008) in Boston is unusual in undertaking an initial cost-effectiveness analysis of adaptation options, including both "hard" defence-based options and "soft" accommodating, pre-emptive approaches such as land use changes and waste water treatment schemes. The "soft" options are largely comprised of no-regret actions and were therefore found to be more cost-effective. A similarly inclusive approach is adopted by the UK Environment Agency, in assessing flood risks in the Thames Estuary for London (Environment Agency (forthcoming). It finds that spatial planning and emergency preparedness will have an increasing role to play in reducing the risks associated with development in the defended floodplain

Other studies that have a city focus include those on mega-cities, e.g. Nicholls (1995) and Klein et al (2003), on New York, (Rosenzweig and Solecki et al (2001; 2006)), and the London Climate Change Partnership in London (LCCP, 2002), both discussed below, as well as OECD (2004) in Alexandria. Many cities that are vulnerable in South and East Asia, and are the subject of ongoing work[3]. There is also high vulnerability projected for many cities in Africa, though outside one or two countries, far fewer sea-level rise impact assessments. Bigio (2003) considered a number of cities likely to be particularly affected including Alexandria, Egypt; Banjul, The Gambia; Tianjin, China; Jakarta,

[3] ADB-World Bank-Japan Bank International Cooperation Initiative on Climate Impact and Adaptation in Asian Coastal Cities is advancing such work, with several coastal mega cities identified for analysis, including Bangkok, Ho Chi Minh, Jakarta, Karachi, Kolkata, and Manila.

Indonesia; and Bangkok, Thailand. However quantitative analysis to inform adaptation decisions in these and other vulnerable cities is still partial.

A study notable for its attention to adaptive capacity and adaptation options is that undertaken by Sherbinin et. al. (2006) who compare the climate vulnerabilities of three coastal megacities: Mumbai, Rio de Janeiro and Shanghai. They use the Canadian Climate Centre's B2 and A2 climate scenarios and project sea level rise of 50cm as well as quarterly mean changes in temperature and precipitation in 2050 for the three cities. They then undertake qualitative vulnerability assessments combining system characteristics and climate and socio-economic stresses. The study provides a valuable illustration of the context-specific nature of adaptation responses likely to be most appropriate, and the implicit limits to the geographical transferability of city study results.

For Mumbai the authors quote TERI (1996) who estimate that a 1-metre rise would result in $71bn damages without dykes, reduced to $33bn with dykes. A 50cm rise in sea-level rise would render informal communities uninhabitable; as a result of coastal shifting there is also structural instability of infrastructure built on landfill. Adaptation possibilities currently consist of shifting the old city to adjacent suburbs or to Navi Mumbai. The authors identify weaknesses in adaptive capacity in an institutional sense; there is a Disaster Management Plan but no proactive measures were being taken at that time. The study outlines that action could be advanced through the ability of informal institutions such as the national slum dwellers union, and overseas support from the country's diaspora to initiate pre-emptive measures.

In Rio de Janeiro, Sherbinin et al (2006), find that sea-level rise concern is focussed on increasing rates of coastal erosion and the higher nourishment costs in order to avoid potentially negative tourism impacts. A reduced capacity for wetlands to act as a buffer against storm surges is also identified, together with greater risks of algae blooms and landslides. The city's vulnerability to extreme events is exacerbated by the fact that – as with Mumbai - the current organisation responsible for disaster management does not (currently) have a remit for pre-emptive disaster preparation. Thus, there appears to be an institutional weakness in developing pro-active adaptation measures such as the revised zoning to restrict construction in hazard prone areas, as suggested by the authors.

In Shanghai, the authors report that sea-level rise is projected to be exacerbated by subsidence and there is also a threat of flooding from the Xangtse river. The vulnerability of buildings is greatest from the shifting ground and the threat of coastal erosion. Current disaster management focuses on the provision of volunteer civil defence networks, though in the future, afforestation and reforestation are highlighted as being potentially effective, along with dyke construction.

Dossou and Glehouenou-Dossou (2007) for Cotonou, Benin, also consider sea level rise impacts and possible adaptation responses. Again, however, the assessment is qualitative. Ng and Mendelsohn (2005) are unusual in quantifying these risks since they examine three sea level rise scenarios to 2100 for Singapore, and investigate whether the city should defend the coast or allow it to be inundated by comparing the value of the area of land likely to be inundated, using sampled land use values, with the costs of dike protection. The study found that, across ten coastal sites representing all market land in Singapore, protection was the lowest net cost strategy.

Built Environment and Infrastructure

The main potential vulnerability of the built environment to climate change is from extreme events; including floods and storms, and to a lesser extent heat-waves and drought (Jollands et. al. 2005). Storms are currently the costliest weather events in the developed world and some research, undertaken principally 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, considering only climate change. 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 could increase by \$8 billion at 2005 incomes (0.06 percent of GDP) due to the intensification effect of a CO_2-equivalent doubling alone, in a future, non-specified, time period.

There are far fewer predictions of storm damage risks specifically at a city level, reflecting the difficulty in down-scaling the prediction of extreme events to an appropriate degree, and the high uncertainty in relation to the predicted changes in the intensity, frequency and storm track variations (Solomon et al, 2007) . In its city-level focus therefore, the New York study by Rosenzweig and Solecki (2001) is an exception, using historical analogues to derive annualised losses for different storm frequencies. They calculate projected damages of approximately 0.1% of Gross Regional Product, (GRP), annualised, and a probable maximum loss of 10-25% of GRP for one event. More recent work (Staunton and Ackerman, 2008) has also considered the potential costs to Miami, Florida from hurricane risk and report similar-sized potential increases in damage, in absolute terms.

The potential risk to urban areas from major extreme weather events, e.g. as with Hurricane Katrina and New Orleans, has led to an emerging literature on the wider economic costs of such events, as well as the potential for non-linear or irreversible effects. Hallegatte et al (2007), using a non-equilibrium dynamic model, estimate that the full macro-economic costs of Hurricane Katrina were about 25% more than direct costs alone, giving total damage costs associated with the event of $130 billion. For analysis of the same event, Crowther et. al (2007) use an input-output model to identify the percentage of infrastructure across different sectors that was disrupted or inoperable following the hurricane, and the associated costs at varying times, and over geographical scales, following the event. The potential economic effects of weather extremes have long been recognised in developing countries, where it has been demonstrated how disasters, or a series of disasters, can affect long-term economic growth. Wilbanks et al (2007), for example, note that in many historical events as much as a quarter of national output is lost over a number of subsequent years.

Storm risk is not the only concern. Recent climate modelling projections suggest that in the coming decades global warming could intensify the hydrological cycle and increase the magnitude and frequency of intense precipitation events. Flood hazard may also rise during wetter and warmer winters in some regions, with more frequent rain and less frequent snow (though spring snowmelt floods are likely to reduce (Kundzewicz et al., 2006). Kirshen et. al. (2004) estimated that total losses throughout metropolitan Boston from river flooding would exceed $57 billion by 2100 assuming no adaptive steps are taken, of which $26 billion was attributed to climate change. In this instance, proactive adaptation was found to reduce these costs by 80%. Similarly, Alam and Golam Rabbani (2007) scope vulnerabilities and responses to climate change for Dhaka. They note that the cost of a 1998 river flooding, in combination with a high tide, totalled $142 million, comprising of damages to the built infrastructure, industrial production, the waste & sewerage system, and other utilities. There were also 284 deaths and 190,000 hospital admissions associated with the flooding. In this case, previous events in 1988 had stimulated a flood protection plan which was initiated and undertaken and helped to protect 50% of the city's area in 1998. There are additional measures planned for the future, which may increase the level of protection, though they were not designed to account for future climate change.

A number of historical analogues of city-scale flood events make estimates of the associated economic costs. For example, Compton et al (2002) found four cases where flooding of urban underground rail systems caused damage of more than US$13m, (in Prague, Boston, Seoul and Taipai), and numerous cases of less significant damage in the last ten years (in New York, Fukuoka, Caracas and Santiago).

Most of the preceding focus has been on the potential effects of extremes on infrastructure. There are also risks to infrastructure in colder regions where climate change-induced permafrost degradation of infrastructure and building foundations is projected (see e.g. Burton and Dore, 2001, and Zhou et al, 2007 for discussions of potential impacts in Canada).

Energy

Energy demand is linked to climatic conditions; with climate change there is likely to be a decrease in the demand for winter heating, but an increase is summer cooling, though the scale of these effects is strongly determined by the climatic zone and socio-economic conditions. Indeed, some integrated assessment models (se Downing et al 2005) find that energy demand is the most important economic impact at the global aggregated scale. However, the net effects vary significantly at continental and even country level. For example, in Europe, there are projected to be strong increases in cooling demand in summer particularly in the south, but reduced heating demand in winter, particularly in the north (EEA, 2007b). Similar results are reported for the US, (Hadley et al 2006) and Japan (IPCC, 2001). Moreover, these changes may be exacerbated by the types of energy sources used, since whilst winter heating demand is more associated with primary fossil fuel use, summer cooling is associated with electricity demand, which may lead to additional GHG emissions, depending upon the fuel type for generation.

These effects are exacerbated at the city scale, in part because of the concentration of business and residential populations in cities, but also because of urban heat island effects which have the potential to exacerbate cooling demand. A number of city studies have undertaken quantified assessments of the likely changes in energy demand. In Athens, for example, Giannakopoulous (2006) estimated a 30% increase in energy demand by 2080 during July due to air conditioning, whilst 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). Estimates made by Kirshen et al, (2008) for Boston produce broadly similar changes to these previous studies. Using regression analysis under a number of climate change scenarios, they project future energy use and estimate that by 2030, the average number of days in July requiring air conditioning may increase by 25% with a corresponding rise in energy use The authors also commented on the reduction in winter heating, but highlighted that while overall winter/summer energy use may not change significantly in net physical energy terms, there could be net economic consequences as a result of price increases to meet the large capital costs needed to expand the system to shift from winter to summer electricity peaks.

It is clear that these effects will be more important in hotter climates. For example IPCC (2001) notes that space cooling is already a major concern in tropical and subtropical cities, accounting for as much as 60% of total electricity use in the commercial sector in Hong Kong, and a similar level of all electricity-supplied energy in Riyadh. Similarly, Miller et al (2007) report that in 2004, 30% of California peak electricity demand was attributable to residential and commercial air conditioning use alone.

Quantitative estimation of energy demand changes is, however, bedevilled by uncertainties. Key uncertainties include: determination of prices under uncertain future socio-economic conditions and

GHG mitigation scenarios; determination of the relationships between penetration and technological efficiency, which are strongly income and energy price dependent. The extent of energy demand changes are also determined by the way in which other adaptation measures are evaluated and adopted. Possible measures include alternatives to mechanical air conditioning such as passive ventilation, building design, planning, green or white roofs, etc. and is the subject of an emerging set of design guides (e.g. Shaw et al, 2007). Unlike the assessment of floods and extremes under climate change scenarios, however, energy demand is also defined principally by mean temperature change so that the confidence in the likelihood of these future impacts is relatively high.

Health

Climate change is likely to affect human health, either directly from the physiological effects of heat and cold, or indirectly, through, for example, the increased transmission of food-borne or vector-borne pathogens, or 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). However, whilst there are likely to be increases in heat related mortality, these need to be balanced against the reduction 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 developed countries, and the distribution of costs and benefits across more temperate world regions (Confalonieri et al, 2007).

At the city-scale the increased risks of heat extremes associated with heat-waves and urban heat island effects are at the fore. Consequently, there is a large body of literature emphasising, in qualitative or quantitative terms, the health effects of current heat extremes (and cold extremes) – a recent overview of the methodological aspects of this literature is given by Gosling et al (2009). Many studies focus on current climate variability (and extremes) though an emerging number of studies are now considering future changes with climate. Such quantitative 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 cities, (McMichael et al (2003) and Bambrick et al, 2008), 11 Eastern US cities (Curriero et. al., 2002), and three cities in the US Midwest (Ebi and Meehl, 2007). These studies project increased average annual morbidity and mortality impacts, though several studies (e.g. Kishen et al (2009) for Boston) report that with appropriate adaptation measures, such as heat alert systems, most overall increases could be negated. There is clearly a strong geographical and climatic variation in the extent of these effects. Indeed, Lindley et al (2006), in demonstrating a climate change risk assessment method with a case study in Manchester (UK), uses spatially-disaggregated data relating to climate hazard, population exposure and vulnerability, to highlight the extent of neighbourhood-scale, intra-urban, heat-related health impacts. A further complication is introduced by acclimatisation: populations may, to some degree at least, acclimatise to future temperatures, the extent being determined by spatial characteristics relating to absolute temperature levels and population vulnerabilities, as well as the rate of change.

In addition to these temperature-related events, climate sensitive infectious diseases such as Salmonella have the potential to increase under a changing climate (Kovats, 2003). Studies now exist at the regional-urban scale - see e.g. Bambrick et al, (2008) for Australia. There is far less consideration of other potential health effects such as vector or water borne disease at the city scale, though these are considered potentially important, particularly in developing countries (Confalonieri et al, 2007), where population density is high, current incidence rates are higher, and the scope for disease transmission is correspondingly increased.

As outlined above, the projected increased intensity of heavy rainfall in many areas is likely to make extreme floods more frequent. While the number of deaths and injuries from floods are relatively low in developed countries, flood events do have potentially important effects at a local level, notably on wider well bring (mental health and stress and depression, e.g. see Tapsell and Tunstall, 2006). Again, adaptation is thought likely to be able to reduce exposure to such events significantly.

There may also 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 – not least because of the population size

Data on the costs of surveillance and outbreak control are starting to be compiled and there are identified adaptation strategies that can be implemented by health sectors, most of which are likely to build on well-established public health approaches (Menne and Ebi, 2006). There are already a series of heat alert systems in place in major cities which appear very cost-effective. Further, 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 North America, but potentially important in developing regions.

Water

Climate change has the potential to affect water demand, as well as water availability and water quality. Increases in average atmospheric temperature will accelerate the rate of evaporation and potential the demand for cooling water in human settlements (IPCC, 2001), which could increase overall per capita water demand. However, water supplies may increase or decrease - depending on the change in precipitation and the level of temperature change projected. It will also depend on future socio-economic development and whether any additional supply can be captured or produced, for example, through desalinisation treatment, noting the latter's high energy requirement.

The strong variation by region, country and catchment area make it difficult to generalise about the effects of climate change on cities in this sector. OECD countries or regions have a very diverse hydrological pattern, though there are some projections of regional vulnerabilities. Kundzewicz, et al (2007, WGII) report that semi-arid and arid areas are particularly exposed to the impacts of climate change on freshwater (high confidence). This includes a number of areas in developed countries, (e.g., Mediterranean basin, western USA), as well as developing country regions (southern Africa, and north-eastern Brazil), which are projected to suffer a decrease in water resources due to climate change.

Changes in water demand have, to date, depended strongly on economic growth and societal development. Economic sectors which are projected to be most affected in relation to climate change are: agriculture (changes in demand for irrigation), energy (changes in hydropower potential and issues of cooling water availability), health (changes in water quality), recreation (changes to water-linked tourism), fisheries and navigation, and potential effects on biodiversity (EEA, 2007c). Wilbanks et. al. (2007) highlight that any change in climate that reduces precipitation and impairs underground water resource replenishment would be a very serious concern for many settlements, particularly in arid and semi-arid areas, in regions dependent on snowpack and glaciers, and in settlements with human-induced water scarcity. Water quality may also deteriorate in areas where river flow decreases.

The assessment of climate change effects on water resources ideally requires catchment level hydrological and socio-economic information, often beyond the administrative boundaries of a given city, as well as down-scaled climatic projections, though even then, uncertainties are high. Not surprisingly, there are very few studies at the city scale and these tend to look at overall water availability and responses to decreases in availability, rather than isolating potential climate change impacts. Exceptions include the study for Washington DC by Boland, (1997), which using climate transient forecasts for 2030, estimated increases in summer water use of 13-19% over the 1990 baseline. With socio-economic change added to these results, a doubling of demand was projected. In a similar vein, Shimizu (1993), quoted in Mimura et al., (1998) estimates that in Nagoya, Japan, daily water demand would increase by 10% if peak daily temperatures rose from 25 to 30°C as a result of climate change, net of any socio-economic change. A more recent example, Maunsell (2008), assessed water resources in state-capital cities across Australia and found that under a wide range of climate change projections these major population centres would be required to supplement their water supply system with substantial new water resources through the 21st century, with urban areas in Western Australia and South Australia likely to be the most severely affected by climate change. Water resources are also becoming an increasing focus in the USA at state, and increasingly city, level (Pew Centre, 2009). However, there are very few studies that cost impacts and adaptation options associated with water supply. An exception is a study in the UK by Wade et al, (2006) who estimated that the economic losses to households of foregone water use due to an anticipated water deficit by 2100 in the region of South-East England could be between £41m ($50m) and £388 m

($450m) annually, depending on climate scenario, but that the costs of largely eliminating these deficits would be between £6 million/year and £39 million/year ($7.5m and $46m, respectively).

Adaptation to changes in climate and socio-economic-induced water availability at a city-scale is explored in a number of studies. For example, Rozensweig et. al., (2007) report the development of a sophisticated analytical response to a projected fall in water availability in New York, which 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 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, (2007), highlights possible adaptation options to meet projected short-term shortfalls in water availability in Johannesburg. Hayhoe et al (2004) and Cayan et. al., (2006), highlight that since there is a significant projected decline in runoff and streamflow from the Sierra snowpack, California's current water rights system may have to be re-designed as a result. For New Zealand, studies of Hamilton (Ruth et. al. (2007) and Wellington (Jollands et. al. 2006) find that, in the medium-term at least, socio-economic pressures arising from population growth and economic development are likely to dominate pressures resulting from climate change.

However, there remains considerable uncertainty in the climate models in relation to average and seasonal precipitation - different models not only predict regional precipitation levels that vary significantly in size, but also in sign - and also extremes in relation to drought and flooding. While advances are therefore needed in the modelling and down-scaling, there is a need for a greater focus on short-term adaptation strategies that increase resilience and enhance coping capacity; subsequent work to consider the potential economic consequences would then be critical in prioritising adaptation actions.

Other Impacts

With projected increases in income and leisure time, the global tourism industry is anticipated to continue to grow. There are existing studies of changes in regional and global tourist flows resulting from climate change. Hamilton and Tol, (2006), using a temperature-based index of attractiveness, report that under a range of socio-economic and climate scenarios, the number of inbound tourists increases for most developed countries. Population growth and economic growth in the rest of the world are projected to bring about this shift in balance whilst climate change acts to increase the rate of growth for in-bound tourism in developed countries, where temperatures are likely to be less extreme. There are also projected to be changes in domestic tourism particularly in developed countries. Other factors are also likely to play a role in influencing visitor number in practice. For example, water shortages due to extended droughts may act with other effects, notably high summer temperatures, to affect tourism flows in the southeast Mediterranean where the largest demand from tourism coincides with the least availability of water resources in absolute terms. More frequent and intense heat-wave conditions may also dissuade visitors away from parts of southern Europe during the summer. Coastal-based tourism may also be negatively affected by increased coastal erosion resulting from sea level rise (e.g. see Awuor, 2008 for Mombasa).

However, city-based tourism is not as dominated by climate. Indeed a significant part of city tourism revenues are currently derived from short-breaks. Nonetheless, cities often act as major gateways for international tourists; they are also home to many cultural assets that provide a focus for much tourism. As an example, there has been analysis of the potential impacts of climate change in Venice, with studies that document the economic costs, (Breil et al, 2005), showing that even very modest sea level rise could lead to increased costs, in the absence of policies to protect cultural assets and other investments.

There are also potential impacts on urban ecosystems or biodiversity, as well as nearby natural resources which could affect recreational opportunities and other ecosystem services. Such effects, however, have received relatively little attention in the literature and few city based studies have been undertaken. An exception is that for Singapore (Ng and Mendelsohn, 2006) which estimated the economic impact of sea-level rise on land that bears no market prices, including beaches, marshes and mangroves, using non-market monetary valuation techniques. They find that local inhabitants attach considerable value to beaches and natural resources, and that protecting such land, whilst found to have sizeable costs, and being potentially harmful to some natural resources, is justified on the grounds of economic efficiency. Wilby and Perry (2006) provide a more comprehensive though qualitative overview of the potential impacts of climate change on urban biodiversity in London. They highlight the importance of four threats to the biodiversity in the city: competition from exotic species; the squeeze on salt marsh habitats from rising sea levels; the effect of drought on wetlands, and; the changing phenology of different species as earlier springs occur more frequently.

Finally, whilst air pollution levels have reduced significantly in recent decades in developed country cities, the health risks of air pollution remain significant (e.g. WHO, 2003; European Commission, 2005). In addition to the local air quality co-benefits of GHG reduction, the direct effects of climate change are likely to be important in relation to ozone, a secondary pollutant formed in atmospheric chemical reactions between hydrocarbons (or VOCs) and oxides of nitrogen (NO_x) in the presence of sunlight. The study by Knowlton et al (2004) in the New York metropolitan area projects increases of 4.5% in mortality rates for the 2050s, due to O_3-related acute impacts from climate change alone. In general, however, the potentially important linkages between climate change and air pollution are only now starting to be investigated.

3. City Level Analysis

As Table 1 indicates, the most quantitatively advanced studies of city-scale climate change impacts are those on London, New York, Boston and Los Angeles (as part of a study on California), and Hamilton and Wellington in New Zealand, though, in all, coverage is invariably partial. By way of illustration, and because their assessments are the most comprehensive, we discuss the series of studies undertaken for London and New York – and listed in Table 2 - in some detail. We then provide a summary of results from a number of other important city studies.

Table 2. 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	Greater London Authority

		heat Island effect	
	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
	LCCP, 2006c	CC Mitigation and Impacts risks on financial services and business	London Climate Change Partnership
	LCCP, 2005b; LCCP, 2007; LCCP, 2008; LCCP, 2009a	Adaptation guidance for commercial and domestic building stock	London Climate Change Partnership
	LCCP, 2009b	Guidance for incorporating adaptation in public procurement processes	London Climate Change Partnership
	LCCP, 2009c	Profiles of recent weather-related impacts on London – Local Climate Impact Profiles (LCLIPs)	London Climate Change Partnership and local councils
	LCCP, 2009d	Impacts on biodiversity resulting from a) climate change and b) adaptation measures	London Climate Change Partnership
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
	New York City Department of Environmental Conservation (NYCDEC), 2008.	Climate Change Programme: Assessment and Action Plan to be finalised by October 2010.	New York City Department of Environmental Conservation, New York City Water Board,
	New York Climate Action Council	Integrated assessment for effective CC adaptation strategies in NY State, including sectoral assessment of costs and benefits of adaptation strategies	New York State Energy Research and Development Authority

It is worth highlighting the institutional and funding structure that led to the evolution of the studies listed in Table 2. Both initial scoping studies arose out of national initiatives in the late 1990s that established the UK Climate Impact. Programme and the US Global Change Research Program, in the UK and the US respectively, designed to scope the impacts of climate change at the regional level and constituted the first city-based studies in each country. The New York scoping study was funded to a limited extent from the national budget by US EPA, but primarily from city-based sponsors. The London scoping study was funded by a consortium of stakeholders, including the Greater London Authority, known as the London Climate Change Partnership (LCCP). 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 LCCP and the New York City Department for Environmental Conservation Climate Change Task Force (NYCDEC CCTF) – charged with co-ordinating cross-institutional adaptation responses. In the UK, the LCCP is one of a number of regional stakeholder groups that were created at this time and which have continued to operate as co-ordinating bodies for research and development of action plans and focal points for dissemination activities. The LCCP, like the other regional stakeholder groups, is comprised of, and funded by, both private and public sector representatives. Both the LCCP and the NYCDEC CCTF also serve to ensure that economies of scale are realised when city boroughs wish to undertake similarly focussed initiatives and that learning from local borough experience is communicated to others.

In both cities, the studies demonstrate that stakeholder involvement has been critical in enchanncing effectiveness. In the initial scoping studies, the establishment of co-ordinating bodies comprising sectoral and cross-sectoral representatives ensured the identification of the most significant sectoral impacts, sectoral impact thresholds and appropriate scale of analysis, and that there existed multi-sectoral financial and human resources available to support research. Subsequently, the role of stakeholders has been to ensure that study findings are disseminated to other sectoral and cross-sectoral partners, that studies are focussed directly on the needs of these stakeholders in developing adaptation strategies, and that financial support has been maintained to support cross-sectoral activities and communication with other interested parties.

The methods and findings of the studies listed in Table 2 are summarised in Table 3. The two tables 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. In both cases, the initial scoping studies were primarily concerned with the identification of potential climate change impacts, and their indicative implications for adaptation actions. This was followed by more focussed studies on prioritised impacts and the development of adaptation plans. In the case of London the foci of the more detailed analyses include the transport sector, flood risks and health risks from heatwaves. The focus on transport and flood risks 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 health effects in both cities reflects increased concerns from the risk of heat extremes and potential exacerbation by urban heat island effects, . 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 scoping studies of the two cities (LCCP, 2002; Rosenzweig and Solecki, 2001a), both using a mix of desk-based and stakeholder consultation approaches, frame the impact research in terms of the quantitative outputs – including changes in 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 forms of sectoral impacts. Quantitative physical estimate ranges were, however, made in the New York study for a number of impacts relating to public health, sea-level rise and energy demand - see Table 3. In contrast, the London study provides estimates of the physical impacts and economic costs of a number of historic extreme events, as well as some projections of future impacts and associated economic costs as these events become more frequent under current climate change scenarios.

Table 3. Summary of key findings from scoping studies

City/Study	Selection of Principal Outputs
London	(LCCP, 2002) Historical cost analogues: Autumn 2000 floods - >£1 billion to UK Industry - £1 million to rail users 2003 heat wave - > £0.75 million to rail users 1987 wind storm - £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. Use of two socio-economic scenarios. 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 general circulation 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 $100-300m annually; with mega-storms causing $100 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. *Socio*-economic scenarios not utilised. 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.

In both studies, the potential responses to climate change impacts described are primarily dictated by sectoral stakeholders. In London, LCCP (2006a) also draws upon comparative analysis that identifies adaptive measures used in cities that currently experience similar climate conditions (now) to those projected for London under future climate change scenarios. However, the uncertainty that resides in impact analysis, from, for example, the range of conditions under alternative climate change scenarios, has so far deterred sectoral adaptation analysis away from probabilistic scenario-based quantification and towards the pursuit of adaptation strategies that utilise options that will be beneficial even in the absence of climate change. For example, City of London, (2006), categorises all identified adaptation options as being no-regret, (benefits outweigh costs under all climate scenarios), low-regret, (low costs and potentially high benefits), win-win (address climate risks and also result in other benefits), or flexible (in responding to uncertainty under longer term climate change). The resulting options are then evaluated qualitatively. As an illustration, in order to manage 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 that a key feature of the research on adaptation is to identify the principal actors likely to be engaged in implementation of specific adaptation actions.

This example 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). Here, the stepped assessment procedure for adaptation outlined in Table 3 has been developed in 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. Quantitative modelling of existing hydrologic variability, quantitative analysis of climate change impacts – imposed on projected socio-economic change – has subsequently been developed.

Whilst quantitative decision analysis has not been reported to date, it is understood that appraisal of new infrastructure will use cost-benefit studies to estimate net benefits and reduce fiduciary risk. 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 on an aggregated, multi-sectoral, basis, as utilised by integrated assessment models at macro-scales, is not undertaken at the city-scale in these examples, suggesting that there remains the potential for such indicators to be used in a more strategic way within city administrations and beyond.

Finally, as highlighted earlier, some city-based sectoral impacts such as water and food supplies have to be viewed within a broader geographical context, London and New York, need to be seen as global mega-cities with substantial economic importance both nationally and internationally, having assets and operations at risk from projected climate change. Since both cities are major global financial market centres they can also be viewed as competitors with each other. Indeed, the London scoping study makes this competitiveness explicit by sketching out an index of attractiveness. It then attempts to evaluate how climate change impacts may affect its competitiveness vis-à-vis New York and Tokyo. Interestingly, it concludes that on this type of index these cities may suffer more in relative terms than London.

4. Conclusions and Research Recommendations

This paper presents an overview of an emerging literature that addresses climate change impacts at the city-scale, and the formulation of appropriate responses. A focus of the review is to assess the extent to which quantitative and monetary measures of impacts and adaptation have been developed to communicate the size and extent of city-level climate risks and to aid cost-effective and cost-efficient responses at this spatial scale. In this final section we summarise the main strands of our findings and outline the implications they have for the design of future research to inform risk assessment and adaptation strategy at the city-scale

The study of potential climate change impacts at the city level, and responses to these risks, is a relatively new phenomenon, though it fits within a general trend in climate impact and adaptation assessment towards a more local scale analysis. This trend is, in part, due to the growing sophistication of climate modelling that allows for increasingly robust ways in which to down-scale climate change scenarios. It may also reflect the fact that climate change policy is increasingly recognising the need to address and adapt to the unavoidable consequences of climate change as well as reducing greenhouse gas emissions. The high population density of cities, their importance for many economic and social activities, and their roles as centres of administrative governance, all highlight the value of city-scale assessments. However, to date, such studies have been primarily in qualitative terms, though quantification of risks is increasing as city authorities and other stakeholders move from raising awareness of these risks to designing responses.

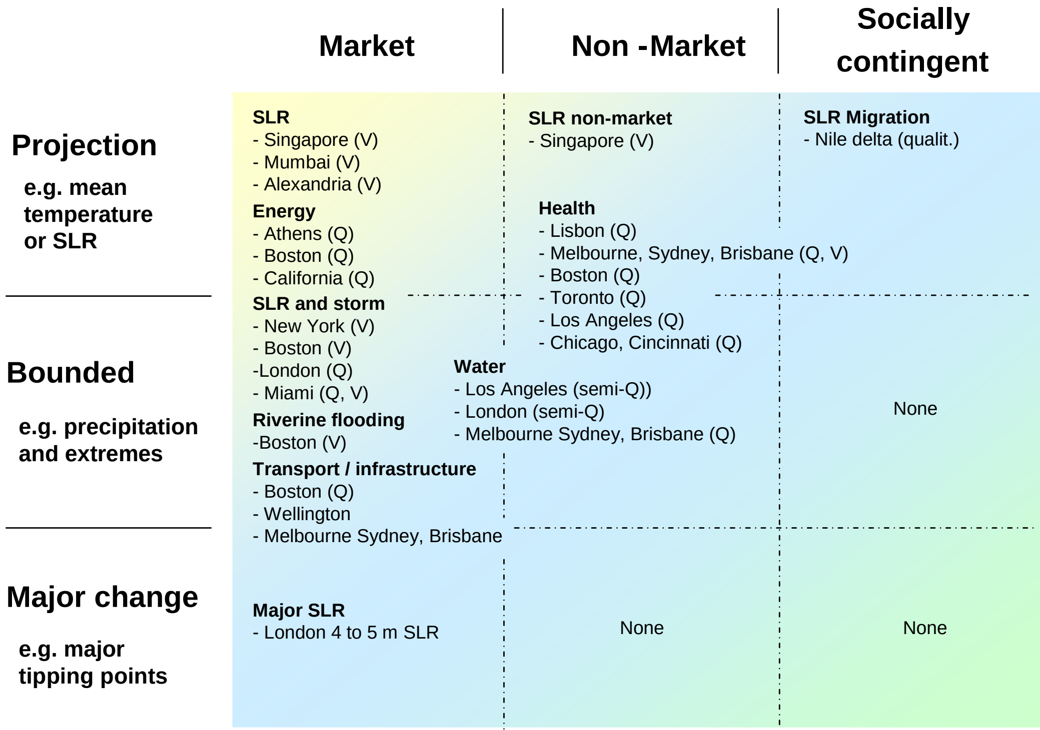
In developed countries, there are now examples where city authorities have undertaken multi-sectoral analysis of potential climate change impacts. The main impacts considered in the studies reviewed are those related to flooding (primarily from sea level rise and storm surge, and to a lesser extent river and intra-urban flooding), public health from heat extremes, and - in more recent studies - water resource availability and energy demand. The focus on these impact categories also reflects the areas where public infrastructure is currently under most pressure from socio-economic development. It also reflects areas where there is greatest sensitivity to current climate variability. This pattern is important in determining economically effective adaptation, recognising that an effective adaptation measure to future climate change may also reduce vulnerability with respect to current climate variability (Fankhauser, 2006). Use of data relating to historical extreme weather events, and their changing frequencies under climate futures, are increasingly used to quantify these risks.

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 and infrastructure investment patterns. Indeed, as the incorporation of climate change risks into water resource planning in the New York City context illustrates, there now exists the capacity to mainstream such risks into city-level socio-economic development strategies. Nonetheless, a significant omission to date has been the recognition of cross-sectoral impacts and adaptation linkages. None of the studies adequately capture these aspects, though the development of lead institutions as indicated for example, for New York and London, is intended to encourage such linkages to be made.

The focus of studies in developing country cities has almost exclusively been on qualitatively-expressed increased flood risks from sea-level rise, reflecting the fact that that the majority of large developing country cities are sited in coastal locations, and that many of them are periodically affected by flooding from coastal storm surge, associated with current climate variability. This focus also reflects the relatively advanced level of analysis that is possible in the case of sea-level rise. However, the often limited understanding of climate risks and the limited institutional capacity that characterise many of these cities have ensured that climate change analysis at the city-scale has generally not progressed further to consider other potential impacts. This is of particular concern given that the evidence strongly suggests climate change impacts will be more severe in these developing countries and perhaps their major cities (Wilbanks et al, 2007). Given these resource constraints, we therefore suggest that increasing standardisation of impact methodologies is likely to be a worthwhile ambition in city-scale studies and more generally in facilitating comparisons. In addition, where public funds for adaptation are distributed on a global basis, resources can be more efficiently allocated when relative vulnerabilities can be compared.

The limited coverage of quantitative impact assessments within city-scale studies is summarised in **Error! Reference source not found.**, based on a risk matrix developed by Watkiss and Downing, (2008). Figure 2 serves to summarise the coverage of monetary valuation of impacts in these studies across different types of effects on human welfare, e.g. market and non-market, and different manifestations of climate change e.g. changes in climate means or the frequency of extreme weather events. Uncertainty in climate projections and monetary valuation estimation increases as we move from the top of the figure to the bottom, and in from the left of the figure to the right, respectively.

Figure 2. Coverage of City Studies against the Risk Matrix



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

Error! Reference source not found. shows that most studies that monetise impacts at city-scale are constrained to impacts whose welfare effects are felt in markets. For example, more demand for energy as a result of greater use of air-conditioning results in increased purchases of electricity, whilst rising sea-levels are projected to result in greater damage to property assets. In the case of non-market sectoral impacts, those in the health sector are relatively well covered in quantitative terms for temperature effects, though much less so for other potential health effects, whilst there is very limited consideration of other non-market categories.

The coverage of other potential effects (both market and non-market) is very low and almost no studies cover socially contingent effects and major/catastrophic events. Figure 2 therefore suggests that since 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, low-cost climatic down-scaling applications are a priority in future research. This constraint is clearly exacerbated at the city-scale, where extremes may be particularly important in determining impacts at the city scale (e.g. see Hallegatte et al., this volume), and where the context is further compounded by local micro-climates and particularly heat island effects.

Although it is clear that climate change risk assessment at the city-scale is in its infancy, there is a sufficient evidence base to allow us to make some tentative suggestions for future city-scale assessments. Specifically, our review highlights the following components as being likely to embody current best practice, building on an earlier outline by Dawson (2007) to identify generic principles underlying urban-focussed climate risk assessment.

1. At the outset, a city-scale assessment should be framed so as not to exclude inter-dependencies – including physical and financial resource flows - with surrounding or wider geographical regions. Similarly, intra-city scale vulnerabilities dictate that the assessment should not be undertaken at the city-scale unit, only. Thus, whilst city-level administrative boundaries are useful to adopt in order to maximise coincidence with public decision-making capacities they should not be used in a dogmatic way. As with climate change risk

assessment practices more generally, it is also important to properly incorporate future socio-economic changes, uncertainties therein being explored in sensitivity analysis.

2. The initial scoping phase of a city-scale climate change risk assessment should be designed to consider all potential climate risks, and should ensure that city-based stakeholders are well represented. Such stakeholder engagement ensures validation of the scoping (and subsequent) phases. To inform subsequent prioritisation, it is likely to be valuable to undertake a qualitative or quantitative ranking of impacts, based on stakeholder elicitation and/or the use of common metrics such as monetisation. Impacts should be grounded in an understanding of existing climatic vulnerabilities. Co-ordination by a lead body additionally allows the pooling of resources for generic aspects of the assessment and facilitates efficient communication of research activities and outputs across the city.

3. Given its relatively resource-intensive nature, quantitative climate risk analysis subsequent to the scoping phase is likely to be best focussed on a small number of risks, prioritised by a previous ranking exercise. Existing stakeholder engagement should then allow these analyses to be embedded in current sectoral risk assessment practices.

4. The evaluation of adaptation responses to climate change risks should be mainstreamed into current sectoral and institutional decision-support practices at the city scale. In this way, the inherent tension between data- and resource-intensive city-level, down-scaled, quantitative analysis, and less resource intensive, qualitative, analysis that highlights vulnerabilities and organisational capacities to respond, may be reconciled on a context-specific basis. It is likely in any case that, following the suggestion of Dawson (2007), uncertainties in climate risk assessment should dictate the adoption of adaptation strategies robust to a wide range of climate sensitivities.

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