Tyndall°Centre
for Climate Change Research

A blueprint for the integrated assessment of climate change in cities

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February 2009

Tyndall Centre for Climate Change Research Working Paper 129

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Abstract

More than half of the global population live in cities, which are major concentrations of vulnerability to climate change. Cities are also major emitters of greenhouse gasses. Consequently they are key to mitigating global climate change and reducing the impacts of climate change on people and infrastructure. This role is being increasingly recognised through the policy and planning measures of individual cities and their collective action in the global climate debate. This paper reviews the potential impacts of climate change on cities and the challenges faced by city planners to manage these risks. An integrated assessment system for analysing climate change in cities is being developed by the Tyndall Centre for Climate Change Research. The principles of this system are introduced before identifying remaining research questions.

Keywords: Cities; Climate change; Climate impacts analysis; Greenhouse gas emissions; Integrated assessment;

Introduction

Urban areas already house more than half the global population and they are expected to continue their rapid growth in the 21st century. Globally, cities are major sources of greenhouse gas (GHG) emissions and their high population density makes them potential focal points of vulnerability to climate change impacts such as flooding, hurricanes and heat waves. Moreover, the influence of a city, in terms of flows of energy, materials and resources, extends far outside the administrative boundaries.

The per capita use of energy in urban areas varies enormously. Attribution of emissions to urban areas is problematic, but cities may be responsible for 80% of GHG emissions. Poorly planned adaptation to the impacts of climate change may induce energy-intensive adaptations, such as air conditioning or desalination of seawater, that undermine efforts to reduce emissions of greenhouse gasses.

Mitigating and adapting to climate change in urban areas involves complex interactions of citizens, governmental/non-governmental organisations and businesses. This complexity can inhibit the development of integrated strategies (which may involve demand management, land use planning and construction of new civil infrastructure) whose combined effect is more beneficial than the achievements of any single agency or organisation acting unilaterally.

In response to these challenges the Tyndall Centre for Climate Change Research has embarked upon an ambitious research programme on climate change in cities, which is developing a quantified integrated assessment model for analysing the impacts of climate change on cities and their contribution towards global climate change in terms of their GHG emissions. This paper reviews the challenges faced by cities and city managers before introducing how the Tyndall Centre Cities programme is addressing some of these challenges. Further research challenges are then identified. These need to be addressed in order to help engineers and urban planners better understand the systems for which they are responsible and support them in the transition to more sustainable urban systems.

Climate change and cities

Urbanisation

Urbanisation is one of the most powerful and visible anthropogenic forces on Earth. Over the 20th century it resulted in humans shifting from being a rural to an urban species and is expected to continue over the 21st century. Urbanisation is driven by social processes that result in an increase over time in the population and/or extent of cities and towns. These drivers may include changes in : population, employment opportunities (in agriculture, as well as in urban areas), services available in citiesand accessibility.

The human race is fast becoming an urban species: cities occupy less than 3 percent of the Earth's land surface but now house just over 50 per cent of the world's population, a figure that was only 14% in 1900 and is estimated to increase to 60 per cent by 2030 (UN 2004a, UN 2004b). The rate of growth in developing countries is faster than in industrialised nations: for example in 1978, 17.9% of China's population was living in cities, yet by 2003 39% of its 1.3billion population lived in urban areas. Currently there are 19 mega-cities (>10 million people); 22 cities with 5-10million people; 370 cities with 1-5million people and 433 cities with 0.5-1million people worldwide (UNCHS 2002). Of the mega-cities, the majority are situated in developing countries and the coastal zone. However, it is usually the medium sized cities that are growing most rapidly.

The most prominent visual features of urbanisation are buildings and infrastructure. However, the influence of urbanisation extends far beyond the urban boundaries. Resources consumed by city dwellers generate an 'urban footprint': land use changes and resource movements between other rural and urban areas that extend far beyond the physical or political urban boundaries.

Urban activities release GHGs directly (*eg*. from fossil fuel-based transport), and indirectly (*eg*. through electricity use and consumption of industrial and agricultural products). Furthermore, a high density of people makes them possible focal points of vulnerability to climate change. Conversely, they also represent concentrated opportunities for adaptation to climate impacts and mitigation of GHG emissions. It is evident therefore that urbanisation is both an outcome and driver of global and environmental change through the interaction of cities with the Earth System.

Climate change impacts in cities

Due to their high concentration of people, business, infrastructure and industry, cities inherently have potential to be hotspots of climate change impacts. Potential climate impacts on urban areas include (IPCC, 2007, DoH, 2001, Hulme *et al*., 2002):

- sea level rise and storm surge flooding;
- river flooding,
- localised flooding due to intense rainfall overwhelming sewer systems;
- building and infrastructure subsidence and landslides;
- wind storm;
- drought and other impacts upon water resources, both in terms of quality (and concomitant implications for health and aquatic ecosystems) and availability for human consumption, industry and neighbouring agricultural areas;
- temperature extremes(as temperatures increase the number of deaths associated with heat stress may be expected to increase, whilst cold related deaths may drop),
- deteriorating air quality; and
- disease (changing profile of vector and water-borne diseases likely to take hold under different climatic conditions).

Some of these impacts directly interact with the urban area (e.g. floods), whilst others are indirect (e.g. climate-induced migration to urban aras). Likewise, some of the impacts of climate change are more readily estimated (e.g. properties damaged in a flood) than others (e.g. marginal changes in vector-borne diseases). However, these climate impacts pose urgent and very real problems. In the 2003 European summer heat wave there were at least 35,000 excess deaths in Europe, primarily in urban areas. Rapid urbanisation that is taking place in flood-prone urban areas, for example the Thames Estuary east of London in the UK, has potential to increase, practically irreversibly, vulnerability to flooding. Eight UK water companies banned garden watering and several applied for special drought powers in the summer of 2006. Despite some high profile flooding events in the last two decades, more people have died from windstorm and since 1950 windstorms have been responsible for almost three-quarters of the UK's insured losses and are as significant in the rest of the world (MunichRe, 2004).

Vulnerability of urban populations

Climate change on its own does not necessarily imply significant harmful impacts in urban areas. Furthermore, a high concentration of population and buildings does not necessarily correlate directly with high vulnerability. The vulnerability of urban areas to climate change is a function of social, economic and political processes. Factors that may influence vulnerability include (Adger *et al*., 2005):

- economic well-being and stability (*e.g*. standard of living; rate of urbanisation);
- demographic structure of population;
- institutional capacity (*e.g*. human resources, adaptive capacity, corruption);
- reliability of social and physical infrastructure (*e.g*. healthcare, communication infrastructure, financial systems, transport infrastructure, business systems);
- global interconnectivity (*e.g*. dependence on trade and tourism); and

- natural resource dependence and regenerative capacity of ecosystems.

Each of these factors makes a contribution to the overall vulnerability or, on the other hand, resilience. Measures to reduce vulnerability may address these factors separately or together, for example by diversification of economic systems or reform of public institutions. A portfolio of measures is usually required in order to have a noticeable effect upon vulnerability by combining diverse approaches ranging from institutional and governance issues to technological systems (such as communication networks) and civil infrastructure (*e.g.* adaptable engineering in construction or refurbishment).

Greenhouse Gas Emissions

The main anthropogenic sources of greenhouse gas (GHG) emissions are summarised in Figure 1. As much as 80% of global greenhouse gas emissions are to urban activity (MunichRe, 2004) and it is therefore appropriate to analyse emissions and develop mitigation strategies at this scale.

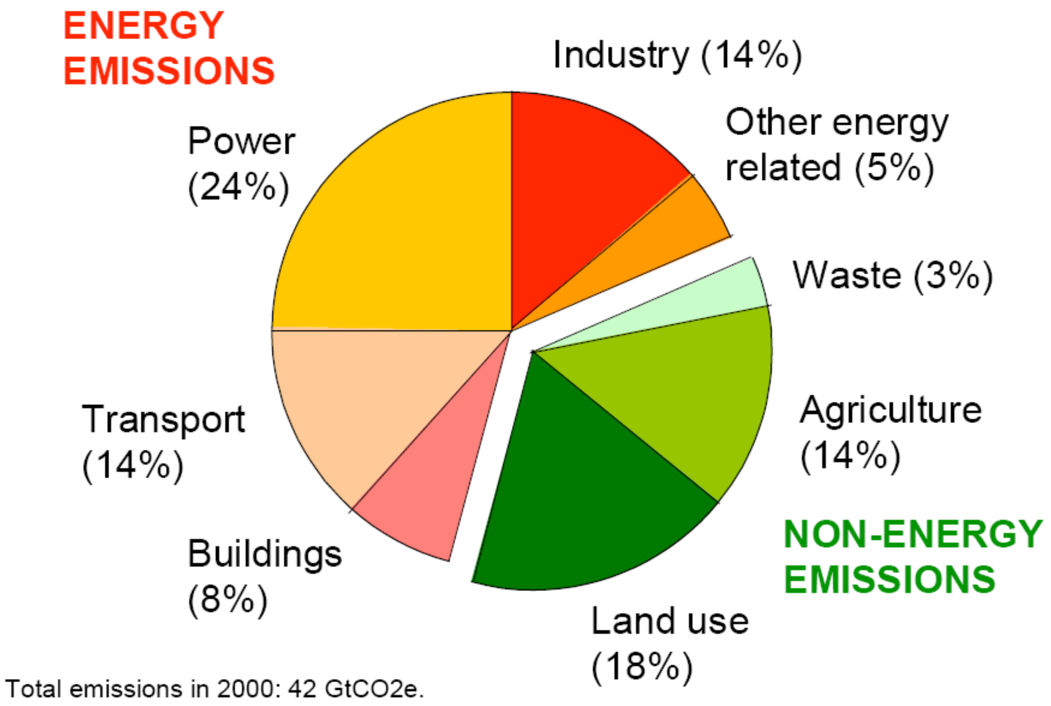

Figure 1 Greenhouse-gas emissions in 2000, by source (Stern 2007)

Adaptation and mitigation at urban scales

Many cities in developed countries are burdened with a legacy of old infrastructure. Whilst in some instances it may be appropriate to build new infrastructure and buildings, in many cases this is infeasible for economic or practical reasons. It is therefore necessary to develop the means to adapt existing infrastructure in order to address climate change, but also other drivers of change including economic competitiveness, population growth, security and health. At a city scale, there are a number of possible adaptation and mitigation options. However, if poorly managed, or not considered at a broad scale over a long time period, responses to climate change can lead to piecemeal, and indeed undesirable, consequences. For example, climate impacts can induce energy-intensive adaptations such as air conditioning, pumped drainage or desalination. These energy-intensive adaptations can undermine efforts to mitigate GHG emissions.

Failure to consider a range of possible impacts over extended timescales can lead to undesirable ‘lock-in’ to specific adaptation options. For example, construction of flood defence infrastructure can lead to intensification of floodplain development that subsequently commits floodplain managers to further flood defence infrastructure as alternatives such as managed retreat become prohibitively expensive and politically untennable. Analysing urban *systems* with evidence-based assessment tools can help cities escape from the viscous circle of increasing climate impacts and emissions.

Designing adaptation and mitigation strategies for large urban areas is made more complex by the systemic effects that emerge as cities grow. It has been recognized for many years that urban areas generate heat islands, which are caused by the storage of solar energy in the city and its buildings during the day and release of this energy into the atmosphere at night. The process of urbanization replaces the cooling effect of vegetated surfaces by imperviously engineered surfaces with different thermal properties. Central heating systems, air conditioning, transport and industrial processes emit heat directly into the urban area, while buildings and infrastructure increase surface roughness that can reduce wind speeds, convective heat loss and evapotranspiration, aggravating the problem further. Warm, still days reduce air quality because high temperatures and ultraviolet light stimulate the production of photochemical smog, ozone and other compounds from traffic and industrial emissions and plants (DoH 2001).

At different scales, different components of the urban system become important: building materials have different thermal properties and subsequent implications for the heat island and roofs can influence airflow locally while the configuration of buildings and infrastructure within the wider urban area has implications for other impacts, such as wind and heat fluxes, flood risk and (waste) water management. High-density cities use significantly less energy per capita on private transport, but generate more intense urban heat islands and can be more vulnerable to other impacts, such as flooding and subsidence. Furthermore, densification of cities can lead to a loss in quality of life for residents.

Mitigating and adapting to climate change in urban areas involves complex interactions of citizens, governmental/non-governmental organisations and businesses. This complexity can inhibit the development of integrated strategies (which may, for example, involve transportation demand management, land use planning and construction of new civil infrastructure) whose combined effect is more beneficial than the achievements of any single agency or organisation acting unilaterally. However, a number of cities have demonstrated that if this complexity can be overcome in pursuit of system-scale responses, then cities can become powerful forces in climate protection.

The integrated assessment framework

In response to the challenges set out above, the Tyndall Centre for Climate Change Research has embarked upon the development of a quantified integrated assessment model to support climate protection decision making at a city scale. On the scale of large cities it is meaningful to think about climate impacts, adaptation and mitigation in the same quantified assessment framework. This is a scale at which strategies for mitigation and adaptation can be usefully designed and assessed. It is increasingly also the scale at which individual civil servants in city administrations are being given responsibility for climate protection. Yet urban climate mitigation and adaptation policy and behaviour can hardly be divorced from its global context. Our framework for integrated assessment, shown in Figure 2, therefore is driven by a global climate and economics models. This provides the boundary conditions for the city scale analysis, in this case study of London. These boundary conditions drive scenarios of regional economy and land use change, ensuring that whilst they are influenced by local policy, these scenarios are also globally consistent. It is at the level of land use modelling that the analysis becomes spatially explicit. Scenarios of land use and city-scale climate and socio-economic change inform the emissions accounting and climate impacts modules. The final component of the framework is the integrated assessment tool that provides the interface between the modelling components, the results and the end-user. These components are discussed in more detail in the following sections.

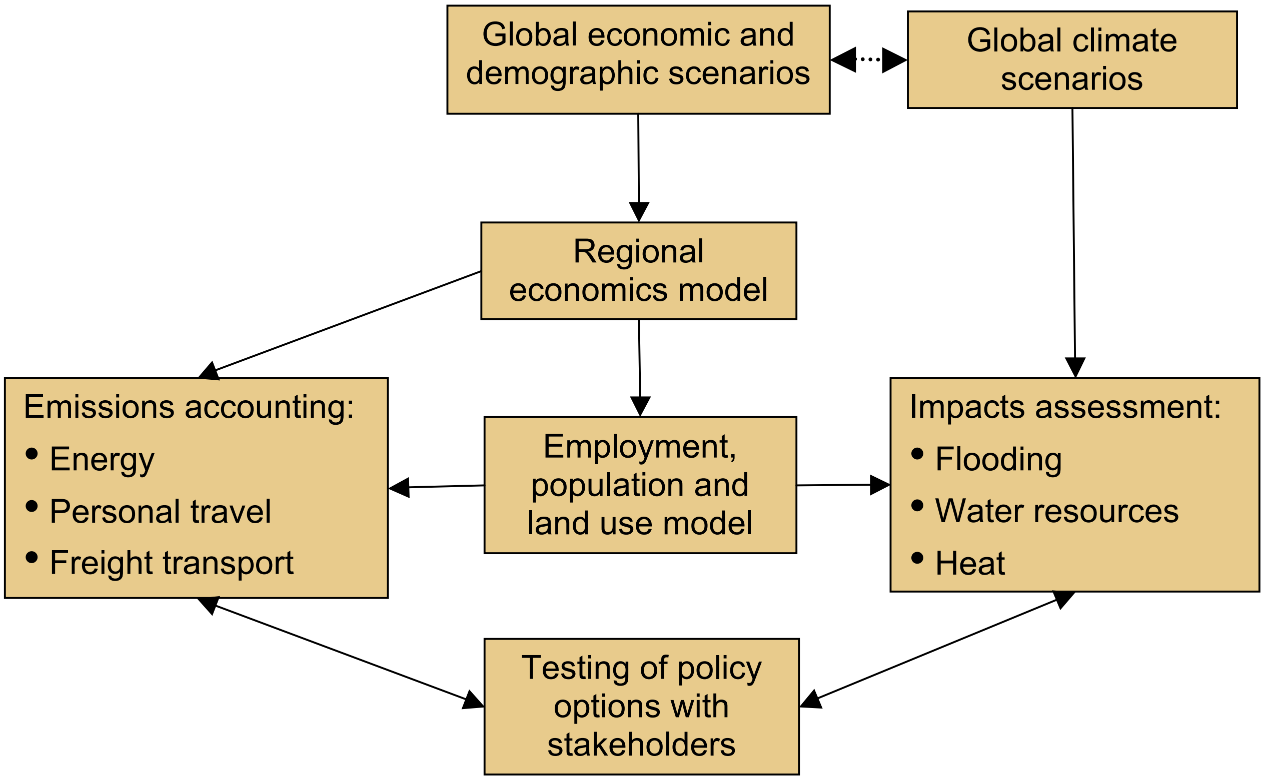

Figure 2 Overview of the integrated assessment methodology for greenhouse gas emissions and climate impacts analysis at a city scale

The framework set out in Figure 2 is intended to be generic for climate impacts and GHG emissions analysis at a city scale. The component models presented in subsequent sections are also generic in that they can, and in most cases have, been demonstrated on other case study sites. However, the framework for urban climate impacts analysis is not constrained by particular models, but in order to implement it a number of key modelling principles are followed:

- The integrated assessment is set within the context of global climate and socio-economic change.
- Global or regional predictions of climate and socio-economic change are downscaled to the urban area, enabling the impact of global GHG mitigation to be explored at the city-scale.
- Within the bounds of a given global scenario, national or city-wide economic and landuse policy can be tested: this does not necessarily have to coincide with the global scenario trajectory.
- Emissions accounting and climate impacts assessment are informed by scenarios of economic and landuse change, whilst being consistent with scenarios of climate change.
- Adaptation and mitigation scenario developed within the integrated assessment must be consistent both internally and within the broader context of global change scenarios (*e.g.* the technologies that may be adopted to mitigate transport emissions at a city scale cannot exceed the assumed level of technological advancement in the global scenario).
- The boundaries of analysis for impacts assessment and emission accounting are not necessarily identical (although always extend at least as far as the urban boundary), but they may often be extended to be more relevant in the context of decision-making (*e.g.* addressing an entire fluvial catchment when considering water resource issues).
- The spatial resolution of analysis may vary according to the process or impact being considered, which may require additional downscaling.
- The integrated assessment considers a finite number of scenarios of global climate change, but allows a more diverse range of city-scale scenarios to be explored.

- To maximise the number of policy questions that can be tested, the models must be implemented such that results are rapidly computed. This can be achieved using a number of approaches including: use of rapid and/or low-complexity models, pre-running a wide range of scenarios and storing the outputs in a database and the construction of model emulators.

A preliminary case study in London

London is the capital city of the United Kingdom and has been a settlement for around two millennia. It has a wide and diverse cultural, social, economic, environmental and built heritage and is one of the most culturally diverse cities in the world with 29% of the population from ethnic minorities, speaking almost 300 languages (ONS, 2003). The population is currently approximately 7.2million and is expected to be over 8.1million by 2016 (GLA, 2004). The London Plan (GLA, 2004) is the strategic plan setting out an integrated social, economic and environmental framework for the future development of London for the next 15–20 years. The plan provides the London-wide context within which individual boroughs (local administrative authorities, of which there are 33 in London) must set their local planning policies. The general aims for London are to:

- Accommodate growth within current boundaries without encroaching on open spaces;
- Make London a 'better' city to live in;
- Strengthen and diversify economic growth; and
- Increase social inclusion and reduce deprivation.
- Improve accessibility through use of public transport, cycling and walking (*i.e.* reduce use of cars, though airport, port and rail infrastructure are likely to be increased);
- Make London a more attractive, well-designed green city through improved waste management, re-use of 'brownfield' sites, increased self-sufficiency and improved air quality.

In the context of climate change a number of policy issues have, through stakeholder consultation, been identified for London:

- The effectiveness, and economic impacts of, taxation as a means of reducing emissions.
- The role of land use planning in reducing emissions and climate vulnerability.
- The effectiveness of regulation and technology at reducing transport emissions from tourists, commuters and freight.
- How to achieve an 80% reduction in non-transport emissions.
- The impacts of climate and socio-economic change on flood risk, water resources and heat stress and how to manage these risks.
- The implementation of cross-sectoral policies that will help reduce climate risks whilst also reducing emissions.
- Uncertainties associated with future climate impacts, emissions and adaptation/ mitigation responses.
- The effectiveness of the timing of implementing response measures, and the effectiveness of different portfolios of responses.

The integrated assessment under development in the Tyndall Centre for Climate Change Research is intended to quantify these issues so as to provide evidence to inform policy decision making. The following sections describe, with the help of some indicative demonstration datasets and outputs, how the integrated assessment is being constructed and what its capabilities will be when it is completed.

Regional economic modelling

A regional economic model is used to provide the quantified economic scenarios that are the starting point for analysis of vulnerability and greenhouse gas emissions. The Multisectoral Dynamic Model (MDM) developed by Cambridge Econometrics has been adopted for the integrated assessment in London. This is a coupled macroeconomic model designed for long term economic analysis based on Keynsian macroeconomic theory, and is described by Junankar *et al.* (2007). The model provides measures of economic activity and employment (Figure 3) in different economic sectors. It takes as its inputs baseline projections of long term growth and population, as well as past observations of the relationships between different industrial sectors. It then disaggregates the long term projections to generate GVA and employment projections for 42 different economic sectors. These provide inputs to the land use model, the transport emissions accounting model and the emissions accounting models described below.

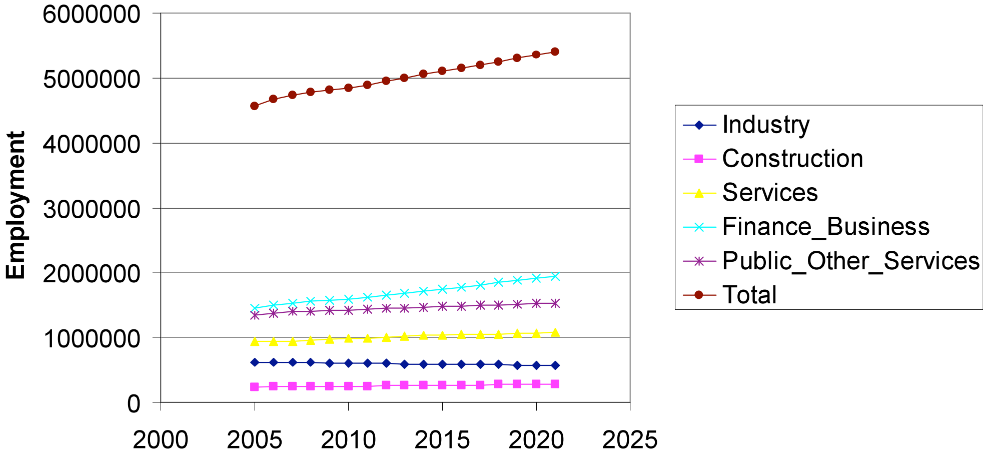

Figure 3 An illustrative projection of economic activity and employment in London, with a projected slight decline in industry but a growth in finance and business employment.

Land use change model

Land use modelling is used to understand potential changes in vulnerability to climate change, as well as transport energy use in commuting. Moreover, spatial analysis of greenhouse gas emissions can help to target mitigation action and may also be a requirement for analysis of air quality and anthropogenic heating contributions to the urban heat island.

The land use transport model adopted in the Tyndall Centre assessment comprises two components. A population and employment allocation model use gravity concepts to distribute different population and employment types according to the ‘attractiveness’ of different administrative zones (known as ‘wards’ in the UK). A key feature of this attraction is the spatial interaction between zones, which is a function of travel time, cost, distance and capacity of the transport network. Planning strategies, such as encouraging development on previously used land or halting development on floodplains allow users to explore how spatial planning can reduce vulnerability to climate impacts.

Figure 4 shows a typical output from the land use change model that indicates the change in employment in different wards of London given the employment changes (and existing transport infrastructure) predicted by the economic modelling. Finer scale outputs are required for meaningful testing of planning strategies and their impact on climate impacts, so a second component of the land use change model disaggregates changes in land use for each ward onto a 100x100m grid (an example is shown in Figure 5).

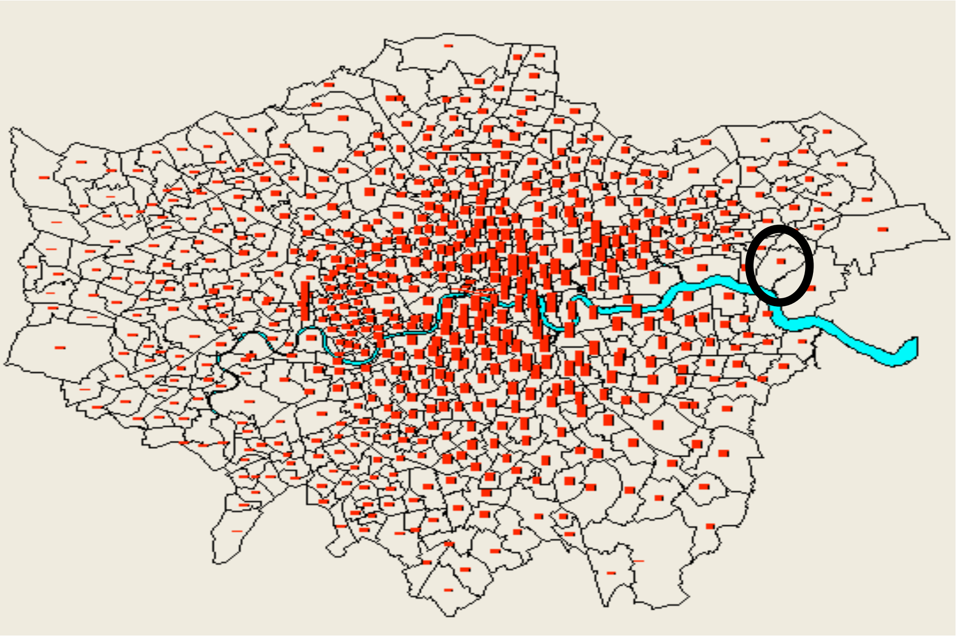

Figure 4 Growth in economic activity leads to increased employment, which can be allocated to different administrative zones according to their 'attractiveness'. Similar results can be produced for population changes. The highlighted administrative zone is studied in more detail in the flood impacts analysis.

Climate impacts analysis

The climate impacts analysis currently focuses on the three most important potential impacts of climate change in London: flood risk, water availability and heat waves. In each case the influence of changing climate variables such as temperature, precipitation and sea level on the risks associated with each impact are explored. In the case of flood risk and water resources this necessitates the modelling of areas outside the city boundary – for example, the water supply to London is in strongly determined by rainfall over the 9,948km^2 area of the river Thames catchment.

In addition to quantifying the impact of climate change, the impact of socio-economic change on risks can be tested. For example, development in floodplains will increase flood risk, whilst increased population and changes to industries and building stock will alter water demand. Against climatic and socio-economic change, the effectiveness of adaptation options can be tested and quantified in terms of their reduction in risk.

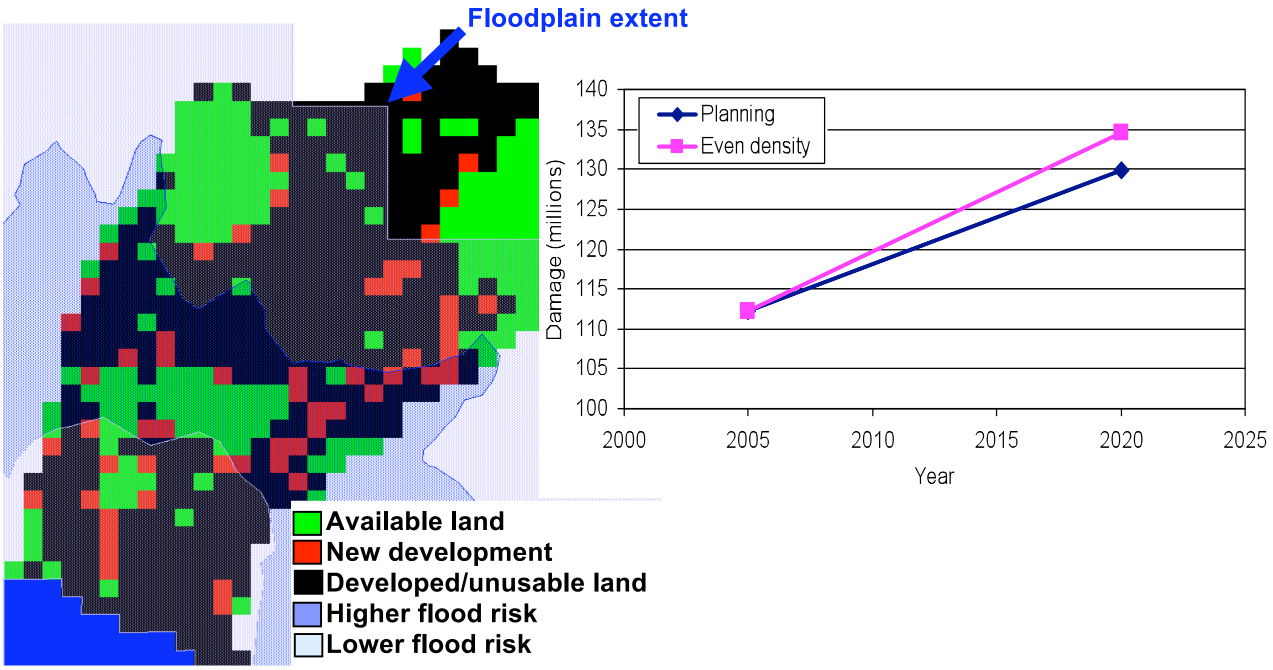

Figure 5 Different planning strategies can influence flood damages. The land use model determines the amount of new development required. For a given amount of growth in a zone that intersects the floodplain (in this case 920 houses and 83 non-residential properties) there will be an increase in flood damages (assuming property damage per property for a given flood depth remains constant). In this example, if the properties are evenly distributed in the development zones then damages increase by ~20%, whilst constraining development to only the lower flood risk zones limits the increase in flood damages to ~15%.

Emissions accounting

In order to better target emissions reduction strategies it is first necessary to quantify emissions and identify their sources. The city-scale emissions accounting tool developed in the Tyndall Centre measures emissions from the following sectors:

- Energy generation,
- Industrial Processes,
- Waste,
- Agriculture,
- Land Use change,
- Personal transport, and,
- Freight transport.

and includes the following GHGs:

- Carbon Dioxide,
- Methane,
- Nitrous Oxide,
- Hydofluorocarbons,
- Perfluorated carbons, and,
- Sulphur Hexafluoride.

The accounting methodology is coupled with a scenario analysis tool to enable users to explore the impact of different scenarios of energy demand, technology change and portfolios of the methods of energy generation used to supply the city. In the case of transport, measures aimed at encouraging behavioural change, such as road user charging, are also being explored. A key feature of the emissions accounting analysis is the ability to explore the cumulative emissions reductions necessary in order to achieve a given emissions reduction target.

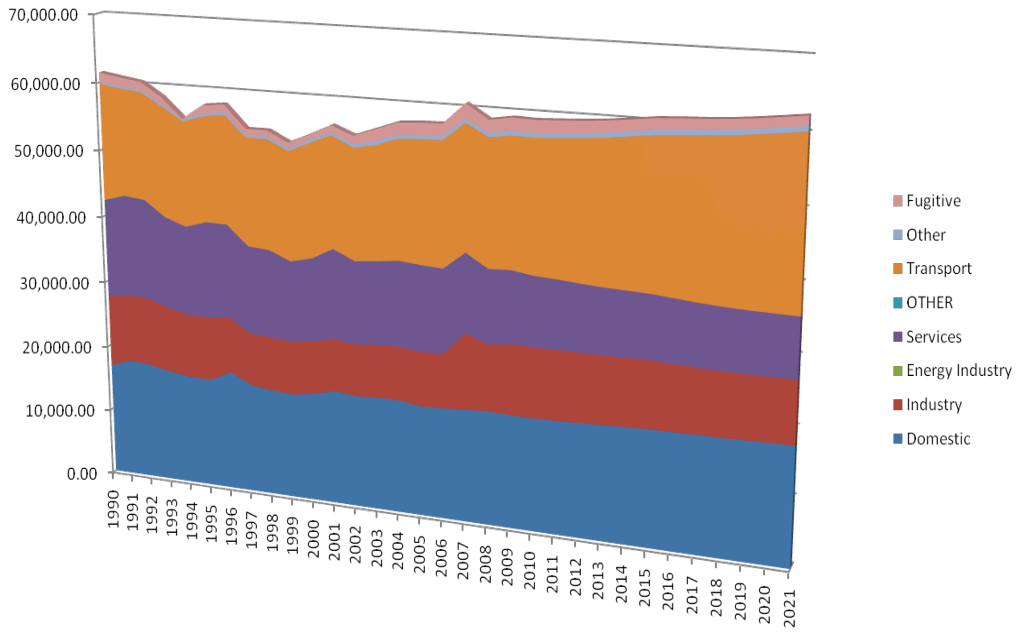

Figure 6 Projections of greenhouse gas emissions from London based on our baseline economic scenario and no mitigation policy

Further research challenges

Whilst there are substantial ongoing research, development and policy related initiatives in urban areas, the research presented here is quite unique because it provides an *integrated assessment* of urban areas that:

- Addresses emissions, impacts, adaptation and mitigation;
- Works on the timescales of major planning and infrastructure decisions i.e. up to 2100;
- Is driven by regional economic and land use modelling, which provides a coherent basis for analysis of impacts and emissions;
- Is coupled with spatially explicit simulations of land use in order to understand key vulnerabilities (e.g. flood risk) and the effects of spatial planning decisions;
- Includes the functioning of engineering infrastructure systems in a physically realistic way;
- Allows portfolios of adaptation/mitigation strategies to be explored in order to identify and exploit synergies and avoid undesirable side-effects; and

However, there remain a number of research challenges that are now considered.

Climate impacts analysis

Further development of this integrated assessment will require incorporation of additional climate impacts models such as windstorm, urban drainage *etc*. The process for generating climate scenarios is based upon statistical downscaling and the use of stochastic weather generators. A more process-based approach is desirable, particularly for analysis of changes in air quality.

A natural extension to individual impacts analysis is to consider cascading failure of infrastructure (and other) components in the urban system. Notably, this analysis should consider implications of changes to the energy supply system such as increased deployment of decentralized and renewable energies, in the context of its robustness and reliability under changing climatic conditions.

Remotely sensed data could be further used to facilitate automation of model parametrization (e.g. identification of roads and embankments). Furthermore, some impacts may require the development of new modelling approaches. For example, modelling of urban drainage and air quality at a broad scale involves computationally expensive simulation of interactions between flow and local features. If these types of models are to be included in risk and uncertainty analyses at an urban scale other than for testing a limited set of simulations, development of emulators, statistical methods or physically based methods of reduced complexity may be necessary. An important consideration, in these cases, is whether urban-scale modelling provides benefits in proportion to the limitations imposed by the additional computational expense.

Urban dynamics

Improved understanding of urban function and dynamics, particularly the multifunctional aspects and relationship with external regions and drivers, will require better understanding of how global and national drivers (e.g. economic, social, technological, climatic change) influence urban change and vice versa. Wider interactions and feedbacks that deserve further consideration include: (i) interactions within the urban area between land use, travel patterns, public and private transport infrastructure and employment and population demography, (ii) the impacts of natural and man-made hazards, climate changes and feedbacks from adaptation and mitigation strategies, and (iii) the interaction between urban areas and changes outside their administrative boundaries.

Urban footprint

Cities interact far beyond their political boundary. For example, declining industrial output has led to reduced GHG emissions in many Western countries, yet these countries still demand large quantities of manufactured goods, leading to emissions being displaced to other parts of the world. Furthermore additional emissions are generated from transporting these goods internationally. Sustainability analysis should build on existing work on analysing the urban footprint to improve accounting of embedded energy in materials and resources that have been manufactured and processed outside the urban boundary and to better understand the relationship between waste handling, recycling, processing, landfill processes and emissions. It is important not to focus on a single metric (e.g. reducing CO_2 emissions) as the only objective because this may lead to unforeseen increases in other environmental impacts.

Decision-support and visualization

Effective decision-making relies upon the engagement of stakeholders, of which there are many in urban areas. New tools for visualization, such as virtual reality suites, are providing a common platform for communication and negotiation. Research is needed in order to develop appropriate tools to support long-term decision-making for a range of stakeholders that also communicate climate impacts, uncertainties, sustainability measures and the wider interactions of a city. These tools and methods must be able to assimilate large quantities of evidence from a wide range of sources. The outputs from the type of analysis being developed in the Tyndall Centre are complex. Whilst decision makers may recognise the benefits of an integrated approach, they are seldom accustomed to thinking through such a complex range of interacting issues and processes. They may struggle to interpret the results of quantified analysis of these processes. The ongoing experience of the Tyndall Centre integrated assessment in London is providing new insights into how computer-based integrated assessment may be used to inform decision making. Further development of tools and interfaces is planning in the light of these experiences.

Conclusions

Urban areas are concentrations of vulnerability to climate change impacts as well as being major greenhouse gas emitters. This is a challenge, but also an opportunity to use urban planning, design and technology to work effectively to reduce vulnerability and emissions. There is rapidly growing understanding within the context of some sectors about the potential for mitigation of greenhouse gas emissions, and in others about strategies for adaptation to climate change. However, this sector-specific understanding is seldom linked up in order to develop multi-purpose strategies for adaptation and mitigation (McEvoy, et al. 2006). The main obstacle to a more integrated approach is the complexity of the decision problems that emerge when a broader set of interactions is considered. Individual decision makers, be they planners or designers, struggle to take account of all of the relevant interactions. Indeed without quantified evidence they will have little basis to evaluate which interactions are relevant to decision making. It is therefore becoming clear that integrated city-scale decision making needs to be supported by quantified integrated assessment tools. In this chapter we have described the principles behind and initial development of one such tool. The core process of interaction between demography, the economy, land use, the built environment and climate are being simulated under a wide range of future scenarios. This provides the basis for testing of policy options and development of strategies that are robust to future uncertainties.

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