

An aerial photograph of London, showing the River Thames and the Tower Bridge, is partially obscured by a large, stylized orange wave graphic that sweeps from the top left towards the bottom right. The sky is filled with dramatic, orange-hued clouds, suggesting a sunset or sunrise.

Engineering Cities: How can cities grow whilst reducing emissions and vulnerability?

Tyndall°Centre
for Climate Change Research

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Foreword

Climate change represents a long term challenge for a great city like London. Ever since the formation of the Greater London Authority (GLA) in 2000, we have been monitoring the science of climate change and working to understand the implications for London. The policies we have implemented and continue to develop, on the basis of science, have the dual aims of reducing London's emissions of greenhouse gasses (roughly 46 Mt in 2005) and protecting London and its inhabitants from the unavoidable impacts of climate change, including floods, droughts and heat waves.

In 2005, when the Tyndall Centre for Climate Change Research first proposed to focus attention on climate change in London, we in the GLA were keen to understand how Tyndall Centre research could complement the studies and policies that we were in the process of developing. It was clear that the systems concept that the Tyndall Centre researchers had proposed had the potential to answer previously intractable questions about how climate change interacts with urban areas. We worked with the Tyndall Centre team to specify questions that we required new science to answer. Those questions have evolved over the four years of research, reflecting the changing policy agenda in London and our improving understanding of the insights that the Tyndall Centre's Urban Integrated Assessment Facility (UIAF as it has become known) can be expected to provide.

As the results summarised in this report indicate, climate change in cities is not a simple story. Cities are complex systems that evolve over a range of time and space scales. Land use, buildings and physical infrastructure change over timescales of decades, so we need to understand the implications of those changes to avoid being saddled with long term problems. The Tyndall Centre research has aimed in particular to understand the implications of climate, population and the economy as drivers of long term change. UIAF simulates the interactions between these processes in order to develop scenarios of change at spatial scales of relevance to decision makers. The work has focussed upon London, but recognises that London is embedded within national, European and global systems of trade, transport, technology and demography. Whilst applied to London, the methods and insights are potentially transferable to cities elsewhere in the UK and the world.

The Mayor has only limited powers to influence how London develops. By mapping out the process of long term change, the UIAF can help us to understand the potential effectiveness of the policy instruments at our disposal and their implications in terms of a range of different indicators, including climate impacts and carbon dioxide emissions. As we work this year to develop the next London Plan, it is particularly important that we understand the synergies and trade-offs between our aims for London to be a prosperous, attractive and sustainable city. We have been pleased that, thanks to NERC support from the Policy Placement Scheme, Dr Richard Dawson from the Tyndall Centre research team has been able to work with us using the UIAF to analyse some of the futures under consideration in the London Plan. We have come to recognise how integrated modelling of the type that is delivered by the UIAF can help to bring different

stakeholders together in order to develop common understanding of processes and consequences of long term change. That collective understanding is essential if we are to manage change rather than becoming its victims.

Getting to a point where the Tyndall Centre research could be brought to bear on policy questions of immediate relevance has required patience. Three years may not be a long time in terms of a research project, but it has been in the life of the GLA. We recognise that generating new insights can take time, particularly in interdisciplinary research teams, of which the Tyndall Centre Cities Programme has been an outstanding example. Through regular advisory meetings and a newsletter reporting interim results, the GLA and other London stakeholders have been able to keep in touch with the research, so that our thinking and that of the Tyndall Centre team had progressively converged during the course of the research programme.

We are still assimilating the insights presented in this report. We have a host of questions (for example concerning pluvial flooding; or introduction of local heat networks) that the Tyndall Centre research has not yet been able to address. We hope that some of these questions will be answered by the follow-on projects that the Tyndall Centre Cities Programme has spawned. For example, the ARCADIA project (Adaptation and Resilience in Cities: Analysis and Decision making using Integrated Assessment), funded from EPSRC's Adaptation and Resilience to a Changing Climate programme, will further develop the UIAF to design adaptation pathways that, step-by-step, can transition urban areas to a more resilient configuration. That, however, is for the future. The purpose of this report is to summarise the results of four years of Tyndall Centre research, which has advanced our understanding of climate change in London and, I believe, is a genuine first in terms of interdisciplinary climate change research.



Alex Nickson

Strategy Manager for Climate Change Adaptation and Water
Greater London Authority



Executive Summary

Cities are concentrations of vulnerability to the harmful impacts of climate change. They are also, directly and indirectly, responsible for the majority of the world's emissions of greenhouse gasses. 50% of the world's population lives in cities, a number that is set to increase to 60% by 2030. For all of these reasons, cities are on the front line in responding to the threats of climate change.

In the UK and around the world there is a growing awareness of the role that cities have to play in mitigating and adapting to climate change. A wide variety of measures are now being considered and piloted, including schemes to transform urban energy systems, reduce transport emissions, retrofit buildings, conserve water, build resilience to flooding and prepare for heat waves. These individual policies need to be implemented as part of an integrated strategy that can steer cities towards low carbon and well adapted futures. To do so requires understanding of the processes that are driving long term change in cities and the ways in which they interact. We recognise demographic, economic, land use, technological and behavioural changes alongside climate change as drivers that will shape the future of cities.

The Tyndall Centre for Climate Change Research has developed an Urban Integrated Assessment Facility (UIAF) which simulates the main processes of long term change at the scale of whole cities. The UIAF couples a series of simulation modules within a scenario and policy analysis framework. The UIAF is driven by global and national scenarios of climate and socio-economic change, which feed into models of the regional economy and land use change. Simulations of climate, land use and socio-economic change inform analysis of carbon dioxide emissions (focussing upon energy, personal transport and freight transport) and the impacts of climate change (focussing on heat waves, droughts and floods). The final component of the UIAF is the integrated assessment tool that provides the interface between the modelling components, the results and the end-user. This tool enables a number of adaptation and mitigation options to be explored within a common framework. The UIAF has been developed for and applied to London, yielding the following insights:

- **Economic drivers of long term change:** A multi-sectoral regional economic model has been used to generate long term projections of employment and Gross Value Added in London. Our base line simulation shows employment in London growing by about 800,000 by 2030, driven by demographic changes and changing working practices. Business and financial services, along with science-based services are expected to grow most rapidly, with heavy industry diminishing.
- **Land use change:** Future patterns of land use between now and 2100 have been simulated for all of London and the Thames Gateway. The new land use model simulates the effects of changes in employment, the transport network and land use planning policy. We have simulated four alternative land use futures for London: (i) a baseline case, which applied current policies and trends in to the future (ii) 'Eastern axis' in which employment opportunities, transport infrastructure development and a preference for lower density living stimulate substantial population growth in east London and the Thames Gateway (iii) 'Centralisation' in which employment and population growth is concentrated in central London, with a corresponding increase in density (iv) 'Suburbanisation' in which employment remains strong in central London, but expands into the suburbs, focused on existing hubs (e.g. Croydon). To steer land use change away from the baseline towards alternative futures requires major shifts in land use planning, transport connectivity and capacity, and employment opportunities.
- **Carbon dioxide emissions:** Various scenarios of carbon dioxide emissions from the energy use, personal transport and freight transport have been analysed. Growth in population, economic activity and mobility are potentially strong upward drivers of emissions. We have analysed portfolios of emissions reduction policies that are currently under consideration, but find that more radical policies are required in order to meet the GLA's target for 60% emissions reductions by 2025. Their success depends upon the availability of carbon-neutral electricity supply and upon progressive physical changes to urban form and function.
- **Heat waves:** A new land surface scheme has been introduced into the Hadley Centre's Regional Climate Model in order to represent the urban heat island effect. Using a weather generator adapted from UKCP09 we found that by the 2050s, one third of London's summer may exceed the current Met Office heat wave temperature threshold. We have analysed the potential for different spatial patterns of development to reduce the risk from heat waves.



- **Droughts:** The UKCP09 rainfall scenarios for the Thames and Lee catchments were combined with catchment hydrology models and simulation of the water resource management system. London is very vulnerable to changes in the surface water regime, which will be increasingly stressed by climate change and population growth. Although new storage facilities can maximise exploitation of the surface water resource, on their own they are insufficient in the long term and will need to be accompanied by vigorous demand management and provision of new resources from desalination or inter-basin transfers.
- **Flooding:** A model of flooding in the tidal Thames floodplain, which is protected by the Thames Barrier and a system of flood defences, has been used to simulate the effects of sea level rise and changing flows in the river Thames. This has been combined with our simulations of land use changes, which have a profound effect on the magnitude of increase in flood risk in the future. The 'Eastern Axis' land use scenario leads to a fourfold increase in flood risk by 2100, whilst the risk doubles for the 'Suburbanisation' scenario. We have tested the effectiveness of various options to improve flood defences and enhance resilience to flooding when it occurs.

By analysing demographic, economic and land use changes, we have quantified the extent to which socio-economic changes determine how hard it will be to reduce emissions and how severe impacts of climate change may be. Indeed socio-economic change over the 21st century could influence vulnerability to natural hazards as much as climate change. The research has demonstrated that **no single policy will enable cities to grow whilst reducing emissions and vulnerability to climate change impacts – a portfolio of measures is required.** Due to long lead times, immediate and in some instances radical action to reduce fossil fuel dependence in the energy, building and transport sectors is required if an 80% cut in emissions is to be achieved by 2050. Measures to reduce demand (in use of energy, transport, water etc.) tend to be more cost effective and less likely to have adverse impacts in other sectors than measures taken to increase supply. However, both supply and demand side measures will be required to respond adequately to the climate and socio-economic changes.

The research has demonstrated the central role of land use planning in guiding and constraining pathways to sustainable urban layout in the long term. Land use profoundly influences carbon dioxide emissions and vulnerability to climate change. It also constrains opportunities for

innovations like sustainable urban drainage systems or local heat networks. Land use and infrastructure planning decisions can become "locked in" because of the way in which infrastructure shapes land use and the built environment, and vice versa. The research has demonstrated scenarios of how these interactions can operate over the 21st century on spatial scales from the whole city and beyond to individual neighbourhoods, providing tools for planners and infrastructure designers to assess the long term sustainability of plans and policies.

We have quantified the synergies and conflicts between adaptation to climate change and mitigation of carbon dioxide emissions, for example by examining the contribution that urban energy use makes to the urban heat island. We have used the UIAF to begin to understand how policies can be devised that yield benefits in relation to a number of objectives and avoid undesirable side-effects.

Throughout the course of the Tyndall Centre research, we have worked with stakeholders in London, including the Greater London Authority, Transport for London, the Environment Agency and Thames Water, to understand the problems facing decision makers in London and demonstrate how the UIAF can help to analyse solutions. Though the research has been based upon London, it makes use of datasets that are available in all UK cities, so the approach could be used to develop and assess responses to climate change in cities elsewhere in the UK. Autonomous local government action will not be sufficient to achieve ambitious cuts in emissions and reductions in vulnerability. Yet the local level is where cities are best understood and where behavioural change can be stimulated. Cities have proved to be places of innovation with respect to climate protection and influential motivators for national government and in global climate negotiations.

Contents

Foreword	1
Executive Summary	2
Cities and climate change: the need for integrated responses	4
London's future: climate constrained or climate ready?	6
Tyndall Centre Cities Research Programme	9
City-scale integrated assessment concept	10
The economy as a driver of long term change	12
Projections of land use change in London in the 21st Century	14
Carbon dioxide emissions from personal transport	19
Carbon dioxide emissions from freight transport	21
Carbon dioxide emissions from energy use	23
Impacts of climate change on urban temperatures	25
Impacts of climate change on water availability	28
Impacts of climate change on flood risk in London	30
Using integrated assessment to inform decision making	32
Data Sources	35
Publications	36
Contributors	37

Cities and climate change: the need for integrated responses

Urban areas occupy less than 2% of the Earth's land surface¹ but house just over 50% of the world's population, a figure that was only 14% in 1900² and one which is estimated to increase to 60% by 2030³. Urban activities release carbon dioxide and other greenhouse gases that drive global climate change both directly (e.g. fossil fuel-based transport) and indirectly (e.g. electricity use and consumption of industrial and agricultural products). Up to 80% of global carbon dioxide emissions are estimated to be attributable to urban areas⁴.

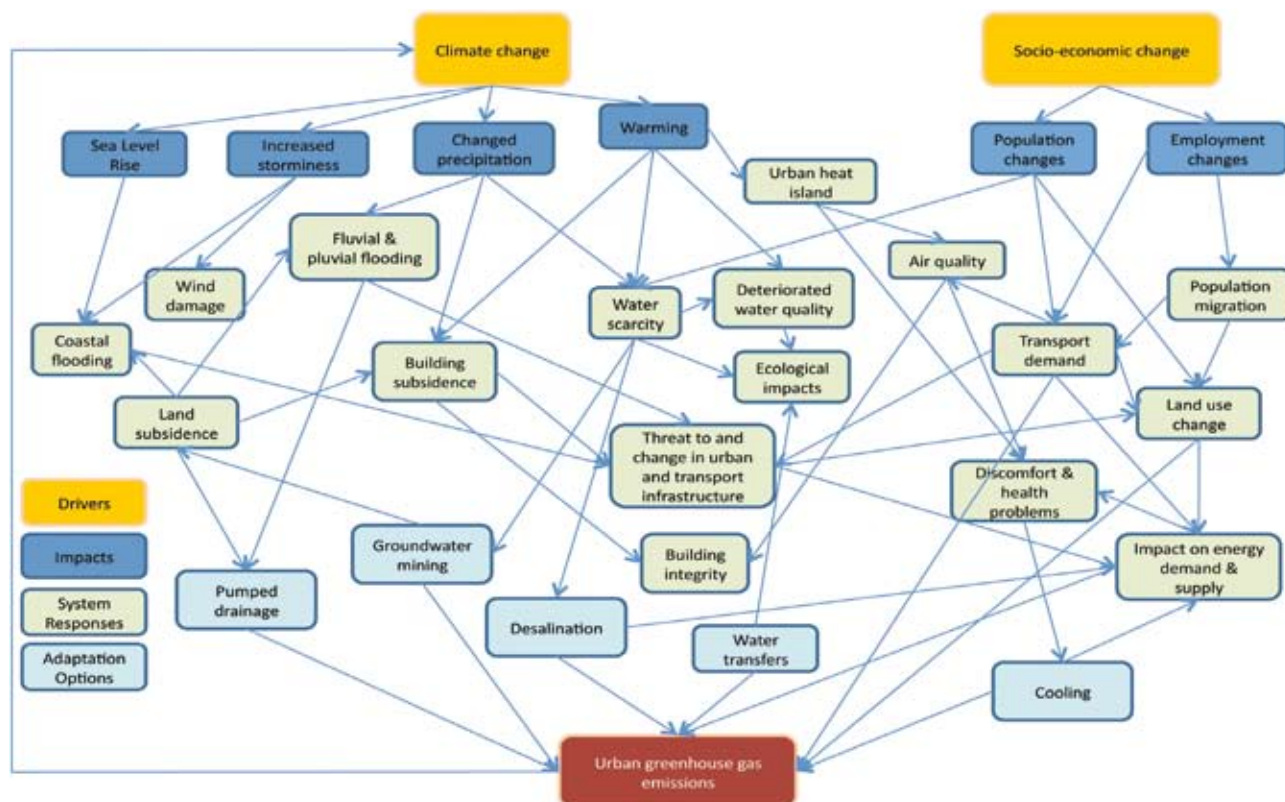
Cities are also potential hot spots of vulnerability to climate change impacts by virtue of their high concentration of people and assets. Potential impacts of climate change in urban areas include: flooding by rivers, the sea or intense downpours, droughts, heat waves by exacerbated urban microclimate (urban heat island effects), deteriorated air quality and damaging storms. These climate impacts will influence economic activity, energy use, health, quality of life and urban ecosystems. The impacts may be felt in terms of changing every-day conditions or increasing frequency and intensity of extreme events such as floods and droughts.

Responding to climate change by mitigating carbon dioxide emissions and adapting to the impacts of climate change is placing new and complex demands upon

urban decision makers. Targets for mitigation of carbon dioxide emissions are now urgent and imply major reconfiguration of urban energy systems, transport and the built environment. Meanwhile, adaptation of cities requires integrated thinking that encompasses a whole range of urban functions.

There is an increasing understanding of the synergies and conflicts in the objectives of mitigation and adaptation. Within cities such interactions occur through land use, infrastructure systems and the built environment. Without careful planning, climate change can induce energy-intensive adaptation such as air conditioning to cool buildings or desalination plants to provide additional water resources. These undesirable outcomes are a consequence of thinking too narrowly about particular problems. If conflicts between the objectives of adaptation and mitigation and, more generally, between economic prosperity and sustainable development, are to be avoided as far as possible then a systems view of cities is required. The systems approach seeks to represent the interactions between different urban functions and objectives.

There is increasing understanding of the synergies and conflicts in adaptation and mitigation.



Some of the many complex interactions and interdependencies between climate change, adaptation and mitigation in cities

- 1 Balk, D., Pozzi, F., Yetman, G., Deichmann, U. and Nelson, A. (2005). The distribution of people and the dimension of place: Methodologies to improve the global estimation of urban extents, Working Paper, Earth Institute's Centre for International Earth Science Information Network, Columbia University (http://sedac.ciesin.columbia.edu/gpw/docs/UR_paper_webdraft1.pdf).
- 2 Douglas, I. (1994). Human Settlements, in W. B. Meyer and B. L. Turner (Eds.), Changes in Land Use and Land Cover: A Global Perspective, pp 149-169, Cambridge University Press, Cambridge.
- 3 UN (2004). World Urbanisation Prospects: The 2003 Revision, New York, United Nations Publications.
- 4 O'Meara, M. (1999). Reinventing Cities for People and the Planet. Wordwatch, Washington DC.

Those interactions play out at a range of different scales, from individual buildings to whole cities and beyond. They also operate on a wide range of timescales. Climate change adaptation has stimulated explicit consideration the implications of choices on a timescale of many decades.

Whilst the endeavour to account for urban functions and interactions at a wide range of spatial and temporal scales is attractive in the insights it provides to decision-makers, it also brings with it considerable complexity. The diagram opposite plots out a sample of the processes whereby climate influences urban function and urban functions interact, in the course of which most of these urban functions emit carbon dioxide, which provides an increment of further forcing to the global climate. These processes of interaction determine how climate drivers will influence urban function. Climate drivers need to be considered alongside other processes of long term change, associated with demography, the economy, technology and behavioural change. The resulting complex set of processes and interactions operate on a wide range of spatial and temporal scales. Some would argue that they defy quantification.

The systems approach seeks to represent the interactions between different urban functions and objectives.

Fortunately many of the tools for representing relevant interactions in cities are reaching greater maturity, though they still require considerable care and interpretation in

their application. Spatial interaction models of the travel migrations within and outside the city help to explain where people choose to live. Regional economic input-output modelling describes the relationship between different economic sectors. Energy systems models simulate the relationship between demand and supply of electricity and gas. The urban heat island and air quality have been the subject of intense research. Well established models exist of water resources and flooding.

Putting these insights together into an integrated assessment that helps to inform decision making has, until very recently however, defied researchers. There are technical reasons for this, but we also recognise the practical challenge of assimilating complex model-based evidence into decision making processes. Yet doing so provides a great opportunity to understand better the potential direct and indirect consequences of decisions,

and to develop portfolios of measures that aim to address a number of different challenges in a synergistic way. Indeed, given the complexity of interactions and the large range of possible futures and decision options, it is hard to see how system-scale policy analysis of long term change could be conducted without the support of computer-based tools.

Planning in general and urban master planning in particular have been out of fashion in the UK for decades – a return to hubristic dirigiste planning is unrealistic. However, we do now recognise that a proper appreciation of the processes of interaction and long term change is necessary to avoid undesirable and unintended outcomes, by a process of “mild but purposeful guardrailing⁵” The uncertainties surrounding future socio-economic, demographic and climate changes may be large, but by exploring the range of possible futures we can identify options that are as far as possible robust to uncertainties. Thus in the Tyndall Centre Cities Research programme we have adopted a philosophy which is basically optimistic about the potential for quantified modelling of urban systems to improve decision making, but humble about the limitations of any modelling activity, particularly when it involves complex socio-technical systems. We recognise that the Urban Integrated Assessment Facility (UIAF) that is described in the following pages will be one of several sources of evidence that decision makers may employ when making difficult and often highly contested choices. Yet we do believe that it provides new insights and tools for policy analysis that were hitherto unavailable and, perhaps most significantly, proves a concept of evidence-based system-scale analysis that shows enormous potential for improving decision making in future.

5 Martens, P. and J. Rotmans, eds. Transitions in a globalising world. 2002. Swets and Zeitlinger: Lisse.

London's future: climate constrained or climate ready?

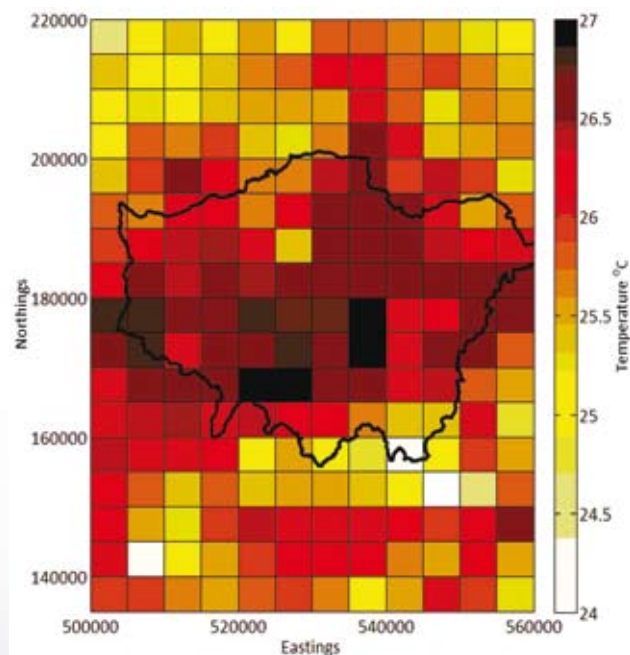
Development of the Tyndall Centre's Urban Integrated Assessment Facility (UIAF) has focussed upon London as the case study. London currently has a population of 7.2 million which is expected to increase to over 8.1 million by 2016⁶. The southeast region of the UK is particularly vulnerable to water scarcity, heat waves and sea level rise. Because of the concentration of population and transport, the southeast is responsible for prolific greenhouse gas (GHG) emissions.

Climate impacts in London

Potential impacts of climate change in London include increased flood risk, water shortages, excessive urban temperatures, air quality problems, wind storms and subsidence.

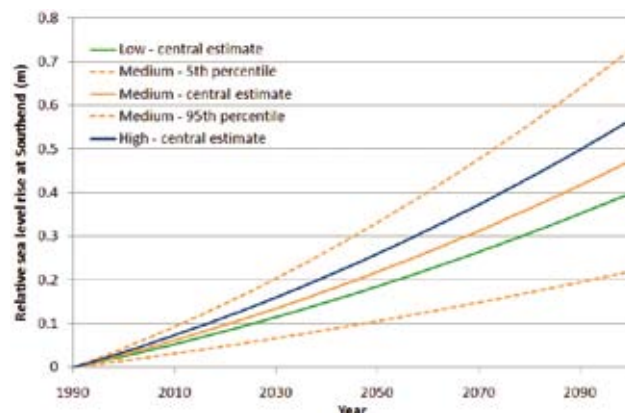
The main potential impacts of climate changes that may affect London are: flooding, water shortages, urban heat and associated air quality problems.

Due to geographical location in the warmer part of the UK and widespread urbanisation, London suffers from urban heat and associated air quality problems⁷.



Met Office Hadley Centre predicted daily maximum temperatures in 2050 for London averaged over the summer season (June, July, August).

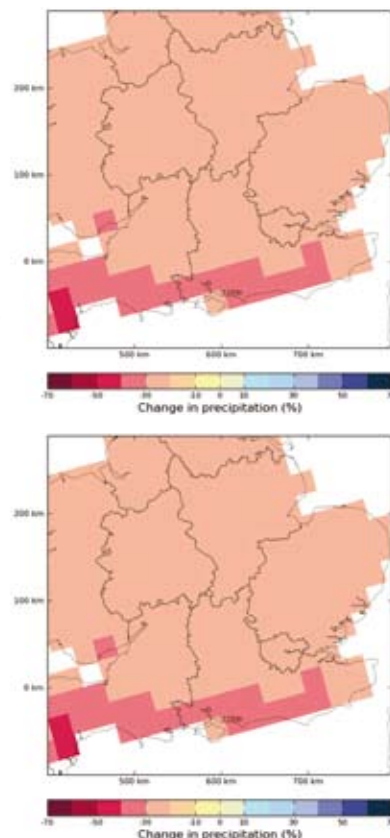
Isostatic subsidence in the south of Great Britain will result in London experiencing faster relative sea rise which, coupled with storm surges, will heighten the risk of surge flooding⁸ in the tidal Thames.



Relative sea level rise projections at Southend⁹.

The southeast is the most water scarce region in the UK, having a lower than average rainfall and a very large demand¹⁰.

Predicted change in summer precipitation in 2050 for the low (above) and high (below) UKCP09 emission scenarios.



⁶ GLA (2004). The London Plan, Greater London Authority, London.

⁷ London Climate Change Partnership (2002), Climate Change Impacts in London: Evaluation Study, Final Report.

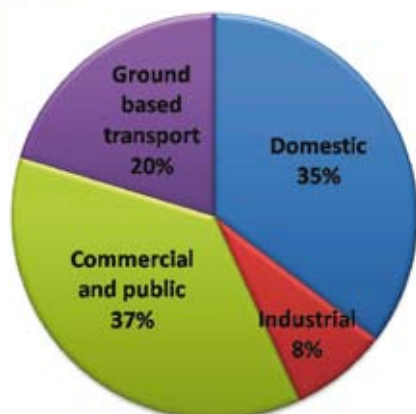
⁸ Evans, E.P. et al. (2004). Foresight Flood and Coastal Defence Project: Scientific Summary: Volume I, Future risks and their drivers, Office of Science and Technology, London.

⁹ <http://ukcp09.defra.gov.uk/>

¹⁰ Environment Agency (2007). Water for the Future: Managing water resources in the South East of England – A discussion document, Environment Agency, Bristol.

Greenhouse gas emissions in London

London is responsible for 8% of the UK's carbon dioxide emissions, producing 46 million tonnes of carbon dioxide each year. Given London's forecast economic and population growth, London's emissions are projected to increase by 15 % to 51 million tonnes by 2025 if vigorous action is not taken to reduce carbon intensity. London's Climate Change Action Plan targets 60% reduction in carbon dioxide emissions by 2025¹¹. Excluding aviation, at the moment domestic, commercial and public buildings contribute the majority of carbon dioxide emissions. Ground based transport contributes a fifth, the majority of which come from cars. Industrial contribution is relatively small and projected to shrink, due to the relatively small proportion of heavy industry in London's economy.



London's greenhouse gas emissions in 2005: 45.9Mt.¹²

Governance in London

London has taken several pioneering steps with respect to how climate change, adaptation and mitigation are dealt with at the city scale. The organisations most relevant to the strategic city-scale management issues considered in this work are The Greater London Authority (GLA), The Government Office for London (GOL), and The London Climate Change Partnership (LCCP). The GLA is a public authority, designed to provide citywide, strategic government for London. The principal purpose of the GLA is to promote the economic and social development and the environmental improvement of Greater London. The GOL liaises with the GLA to ensure that London planning is done within the context of national policy; and leads government responses to the GLA's strategies. The London Climate Change Agency (LCCA) was established in 2005 as the primary delivery vehicle for reducing London's carbon dioxide emissions. The LCCA has now been integrated into the main body of the London Development Agency. The LCCP focuses on assessing the impact of climate change and identifying adaptation strategies. Each organisation has clear responsibilities, which cross sector boundaries. The GLA are in a position to take an overview of strategic issues related to climate change.

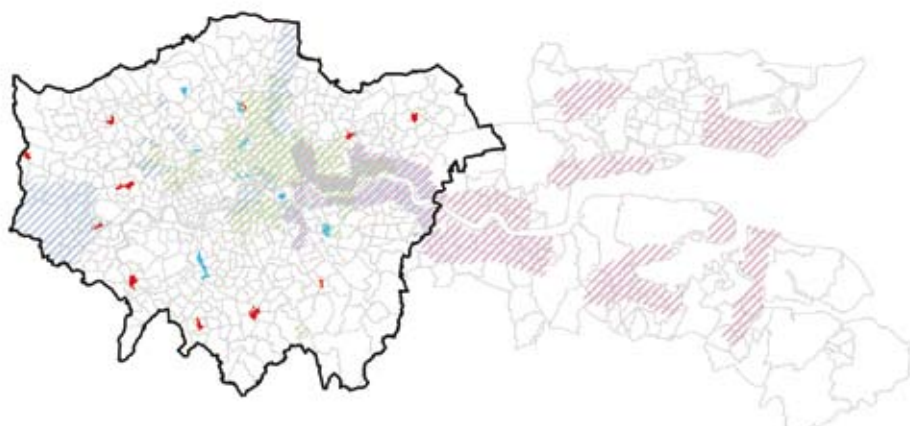
The GLA are in a position to take an overview of strategic issues related to climate change in London.

Zones of development within the GLA boundary and the Thames Gateway (development zone to the east of London) identified within the London Plan and by Thames Gateway Development Corporations.

0 5 10 20 Kilometers

Legend

- GLA Border
- Opportunity areas
- Thames Gateway development zones
- Regeneration areas
- Metropolitan centres
- Intensification areas
- Census ward boundary



¹¹ GLA (2007). The mayor's climate change action plan. February 2007.

¹² London Energy and GHG Inventory (2004-2005). November 2008.

Development pressures in London

The London Plan is the spatial development strategy for London developed by the GLA setting out an integrated social, economic and environmental framework for the future development of London for the next 15-20 years. The Plan highlights areas that are targeted for development, with an emphasis upon development of

To accommodate expected population increase, development zones have been identified as part of the London Plan and within the Thames Gateway.

previously developed land and upon certain areas that are targeted for regeneration. The Thames Gateway is a 40 mile tract of land that stretches from the London Docklands to the Thames Estuary. The Gateway has been targeted for significant development over the coming decades and will host the Olympics in 2012. By 2016, 120,000 new households and related

infrastructure will be developed in the Thames Gateway area^{13, 14}. Only part of the Thames Gateway falls within the boundaries of the GLA but given its strategic significance in particular with regard to flood risk, it has been included in our assessment. The tidal Thames floodplain includes extensive areas of development including many existing residential, public and commercial buildings as well as transport infrastructure. These areas are incorporated in the land use modelling component of this analysis and some of the policies outlined in the London Plan have been tested with the UIAF.

In addition to climate impacts, emissions reduction targets and development issues, London as in any city has a range of broader interactions to consider. For example, waste management which affects greenhouse gas emissions and energy generation. London is rich in biodiversity habitats, given its green space and aquatic environments.

Like all major settlements, London is not an isolated city and interacts strongly with the rest of the UK, Europe and the rest of the world. Interactions occur through a complex network of flows of energy, transport, materials, food, waste and water. Broader issues of sustainability, resource use and urban footprints need to be considered alongside the challenges of climate change addressed in this report.

¹³ ODPM (2003). Sustainable communities: Building for the future, Office of the Deputy Prime Minister. (www.communities.gov.uk).

¹⁴ ODPM (2004). Creating sustainable communities: Greening the gateway, Office of the Deputy Prime Minister. (www.communities.gov.uk).

Tyndall Centre Cities Research Programme

In 2006 the Tyndall Centre for Climate Change launched a research programme on climate change in cities. The aim of the programme was to develop a quantified integrated assessment model for analysing the impacts of climate change in cities, alongside their contribution towards global climate change in terms of their carbon dioxide emissions. Given the Tyndall Centre's track record in integrated assessment modelling at a global scale, and more locally in the coastal zone, the Centre was in a strong position to address the new challenge of dealing with cities, which in many respects are in the 'front line' for tackling challenges associated with a changing climate. The Tyndall Centre partners involved in this research (Newcastle, Manchester and Cambridge Universities and the University of East Anglia) joined forces with partners outside the Tyndall Centre (the Met Office Hadley Centre, Leeds and Loughborough Universities and University College London) with relevant expertise in climate, transport and spatial systems.

Programme objectives:

- Develop and demonstrate a downscaling methodology for generating scenarios of urban economic indicators, land use.
- Develop and demonstrate a city-scale greenhouse gas emissions accounting tool.
- Adapt and apply methods for city-scale climate impacts assessment.
- Evaluate, in city-scale assessments, strategies and technologies for reducing the impacts of climate change and greenhouse gas emissions.



The programme was led by Professor Jim Hall (Newcastle University) and was divided into six tasks with the following researchers contributing to these tasks:

1. Development of a blueprint for integrated assessment of urban systems:
Richard Dawson and Jim Hall (Newcastle University)
2. Development of a land use model of London:
Stuart Barr and Alistair Ford (Newcastle University);
Mike Batty and Stephen Evans (UCL)
3. Economic simulation and scenarios:
Athanasios Dagoumas and Jonathan Köhler (Cambridge University).
4. Development of a City-scale emissions accounting tool:
Sebastian Carney (University of Manchester).
5. Development of a Transport policy appraisal and emissions accounting tool:
Miles Tight and Helen Harwatt (Leeds University),
Abigail Bristow and Alberto Zanni (Loughborough University)
6. Evaluation and implementation of impacts assessment modules
Richard Dawson and Claire Walsh (Newcastle University); Clare Goodess, Colin Harpham and Phil Jones (UEA); Mark McCarthy and Michael Sanderson (Met Office)

The various components of the programme are integrated in Task 1 as The Urban Integrated Assessment Facility (UIAF) which brings together long term projections of demography, economy, land use, climate impacts and carbon dioxide emissions within a coherent assessment framework. It thereby provides the basis for examining at the scale of whole cities the effect of adaptation and mitigation decisions, with a particular emphasis upon decisions with an extended legacy.

A group of key stakeholders from the GLA, Transport for London, Environment Agency, Thames Water, alongside academic mentors from Durham University and University of East Anglia was convened in order to:

- Advise upon existing studies and tools and establish how our work was complementary
- Provide access to relevant datasets
- Identify policy questions that the research could usefully address
- Identify policy options to be analysed

City-scale integrated assessment concept

Integrated assessment has been applied to a wide variety of different systems and at a range of different spatial and temporal scales. Here our attention is upon cities. The timescale of appraisal is taken as being up to a century into the future. Our interest is in long term processes of change and on how climate-related drivers inter-play with other drivers (for example demographic and economic processes of change) over these timescales. This extended timescale coincides with the typical time frame for assessment of climate change policy. An extended time-frame is also motivated by the long life of infrastructure systems and the extended legacy of planning decisions. It is these major planning and design decisions that we are seeking to inform so as to avoid decisions with consequence that are materially regrettable or foreclose the opportunity for alternative actions in future. Of course on this timescale there are major uncertainties, so the integrated assessment has to be set within an appropriate uncertainty framework.

To understand processes of change on extended timescales, it is usually also necessary to analyse them on broad spatial scales. Here our analysis is on the scale of whole cities, as it is on that scale that patterns of spatial interaction are most vivid. Moreover, cities are administrative units for planning and decision making. However, framing the city in this way brings inevitable boundary problems. Thus we seek to represent the economic and transport interactions between the metropolis and the surrounding region and nation. In fact to analyse water resources and flooding we must examine the whole of the surrounding river basin, together with inter-basin transfers where they exist. Other aspects of urban climate require a nested approach to downscaling from the global climate. The boundaries that we set are therefore multiple and not always coinciding, though they all have a certain rationale in the context of this city scale analysis.

Integrated Assessment enables:

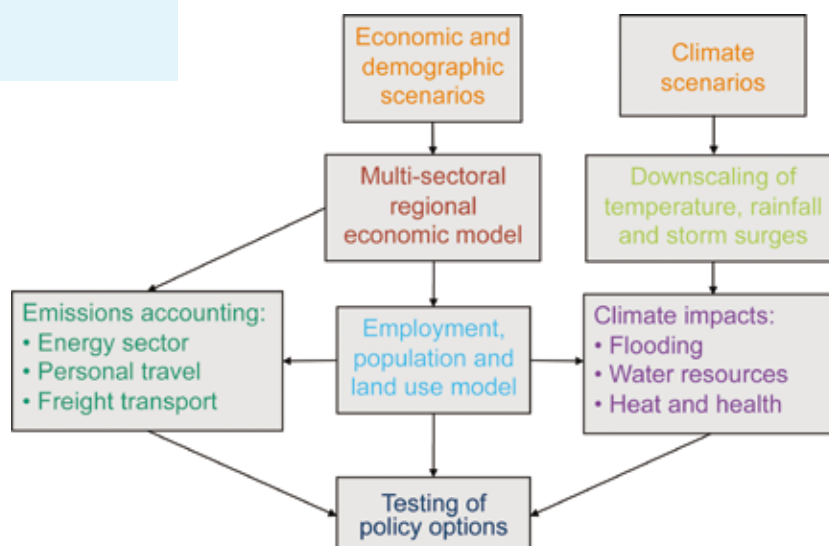
- A whole system approach
- Representation of relevant interactions
- Internal consistency
- Analysis of multipurpose policies

The overall structure for the integrated assessment is shown below. Each element is described briefly now and in more detail in the following sections of this report. At the top of the figure are the socio-economic and climate scenarios that provide the context for the analysis. A process of down-scaling generates climate scenarios at the city scale as well as economic and demographic scenarios for the urban area. This provides the boundary conditions for the city scale analysis, in this case study of London. A spatial interaction module provides high resolution spatial scenarios of population and land use that form the basis for analysis of carbon dioxide emissions and vulnerability to climate impacts. The modules for emissions accounting and for climate impacts analysis are depicted on the left and right sides of integrated assessment, respectively. These provide projections of emissions and climate impacts under a wide range of scenarios of climate, socio-economic and technological change. The Urban Integrated Assessment Facility (UIAF) provides the flexibility to test a very wide

The integrated assessment involves:

1. Socio-economic and climate scenarios provide the context for the analysis;
2. A process of downscaling from regional generates climate scenarios at the city scale;
3. A regional economics model generates scenarios of employment in different sectors
4. A land use model generate scenarios of land use change across the city;
5. Scenarios of changing vulnerability are combined with downscaled climate variables to analyse the impacts of climatic change;
6. Emissions accounting tools for the energy and transport sectors provide analysis of carbon dioxide abatement options;
7. The integrated assessment tool provides the interface between the modelling components, the results and the end user.

The analysis is conducted on a timescale out to 2100 for all of London.



range of mitigation and adaption policies, including land use planning, modifications to the transport systems, changing energy technologies and measures to reduce climate risks.

The analysis has been brought together in an integrated assessment tool. The purpose of the tool in the first instance has been to enable the research team to conveniently generate and display results, as part of the testing and verification of the model. The tool is now being used to provide scenarios for the Greater London Authority. An extended range of scenarios and policy options are being developed in consultation with the GLA to test options outlined in The London Plan and to answer policy questions that were identified at the start of this research programme.

Scenarios and policy options

Scenarios represent alternative storylines of the future rather than predictions or forecasts. Scenario analysis is appropriate in situations of severe uncertainty about the future as it enables exploration of a wide range of possibilities. Whilst scenarios represent no more than possible or plausible future, it is important to ensure that they are internally consistent. Typically, scenario studies have focussed upon a relatively small number of scenarios. Here, because of the flexibility of the UIAF, we are able to analyse a wider range of possible futures. The main dimensions of our scenario space are:

1. **Economic growth**, using a range of GDP scenarios for the UK
2. **Population**, using Office of National Statistics Subnational Population Projections
3. **Climate change**, using the 2009 UK Climate Projections¹⁵

The UK Climate Projections (UKCP09) are based on a new methodology which include quantification of some uncertainties in the projections. A range of greenhouse gas emission scenarios (High, Medium and Low) are analysed out to 2100.

At a city scale there are a range of different policy options including

- land use planning;
- investment in transport infrastructure;
- measures to adapt to the impacts of climate change;
- measures to mitigate carbon dioxide emissions.

These are the policy options that we focus upon in the analysis.

To summarise, the analysis refers to both scenarios and policy options. Here scenarios are used to represent processes of change that operate at a broader scale than the city i.e. economic, demographic and climate scenarios. At the city-scale, adaptation and mitigation options are to some extent under the control of local decision makers so we refer to them as *policy options*. The separation of exogenous scenarios and city-scale policy options is to some extent artificial, as urban policy develops in a national and international context, not in isolation. Furthermore, processes of long term change at a national and global level are influenced by changes taking place in cities. However, broadly speaking, we wish to test the effectiveness of city-scale policies in the context of a range of possible futures at a national and global level. We achieve this by separating exogenous scenarios from local policy options.

15 <http://ukcp09.defra.gov.uk/>

The economy as a driver of long term change

What we did:

A multi-sectoral regional economic model was used to provide quantified economic scenarios (employment, Gross Value Added and energy demand) that are the starting point for analysis of and carbon dioxide emissions and vulnerability to climate impacts.

A multi sectoral regional economic model called MDM-E3¹⁶ has been used to generate economic scenarios. MDM-E3, is the UK's most detailed, integrated energy-environment-economy model. The model is a coupled macro-economic model of the whole economy, but is multi-sectoral, so predicts output from and employment in 42 different industrial sectors. It is a model of growth and fluctuations over the medium and long term, so is well suited to the task of providing internally consistent scenarios for the purpose of integrated assessment. The model is dynamic, providing intermediate results at time-steps over the simulation period. It takes as its inputs baseline projections of long term national GDP growth and population, as well as past observations of the relationships between different industrial sectors.

MDM-E3 is a dynamic simulation model, putting an emphasis on 'history', as it is based on time series and cross-section data, using input-output data from Office of National Statistics (ONS). One major limitation of this approach is that it takes projections of the existing relationships in the economy into the future; therefore it does not consider any major structural changes for example due to mass population migration or a financial collapse. Moreover, the model response is smooth and does not contain a stochastic process, so does not represent the possibility of sudden fluctuations in the economy.

Whilst MDM-E3 has been used for many years to generate economic forecasts and has been well validated,

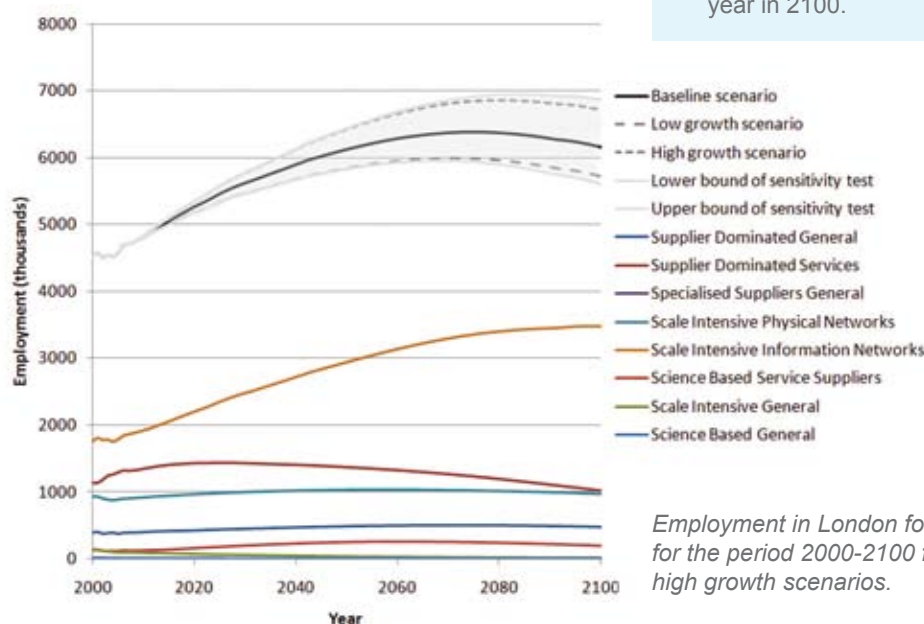
the extended timescale of this analysis exceeded that of previous MDM-E3 simulations. The model was therefore extended up to 2100 in order to provide output tables of

1. economic activity with regional and industrial disaggregation (measured in terms of economic value added at constant prices),
2. employment with regional and industrial disaggregation (measured in terms of full-time-equivalent employees)
3. energy demand (in terms of thousands tonnes of oil equivalent consumed by different fuel type) at national level with industrial disaggregation.

In order to understand interactions in the neighbouring regions scenarios were output for three regions: London, Southeast England and East England. Three main scenarios were developed, representing base, low and high growth scenarios. A sensitivity analysis was also carried out on the effect of hours worked per week, as this variable contains assumptions about the changing proportion of part-time jobs. In the base case reduction in working hours per week ramps up to a 25% reduction in 2100. Reduction in worked hours means that more part-time jobs are available affecting the full-time-equivalent employment.

Economic scenarios input to the MDM-E3 model:

- I. Baseline scenario:** UK GDP growth rate steadily decreases to an annual rate of 1.5% per year in 2100.
- II. Low Growth Scenario:** UK GDP growth rate at national and regional level is 0.3% less than in the baseline scenario, steadily decreasing to 1.2% per year in 2100.
- III. High Growth Scenario:** UK GDP growth rate at national and regional level is 0.3% higher than in the baseline scenario, steadily decreasing to 1.8% per year in 2100.



Employment in London for 8 aggregate economic sectors for the period 2000-2100 for the baseline, low growth and high growth scenarios.

¹⁶ Barker, T. and Peterson, W. (Editors) (1987). The Cambridge Multisectoral Dynamic Model of the British Economy. Cambridge University Press, Cambridge.

Aggregate Sectors	MDM Sectors
Supplier Dominated General Manufacturing	Agriculture; Coal; Oil & Gas; Other Mining; Printing & Publishing; Necessities; Electricity; Gas Supply; Water Supply; Construction
Supplier Dominated Services	Textiles, Clothing & Leather; Hotels & Catering; Public Administration; Education; Health & Social Work
Specialised Suppliers General	Mechanical Engineering; Other Transport Equipment
Scale Intensive Physical Networks	Distribution; Retailing; Land Transport; Air Transport; Water Transport
Scale Intensive Information Networks	Communications; Banking & Finance; Insurance; Professional Services; Other Business Services; Miscellaneous Services
Science Based Service Suppliers	Computing Services
Scale Intensive General	Food, Drink & Tobacco; Wood & Paper; Manufactured Fuels; Chemicals; Rubber & Plastics; Non-Metallic Mineral Products; Basic Metals; Metal Goods; Electrical Engineering & Instruments; Motor Vehicles
Science Based General	Pharmaceuticals; Electronics

Results

The 42 sectors in the MDM-E3 model have been aggregated into eight broad industrial categories, based on their technological characteristics and on the likely effects of three pervasive technologies (information technology, biotechnology and nanotechnology) on their input-output structures^{17, 18}. These 8 categories are likely to remain in the future even if some of the 42 industries that currently define the categories do not. Trends of employment and the economic activity of those 8 aggregate sectors for the baseline, low and high growth scenarios for the period 2000-2100 were calculated.

London is predicted to have a growth rate at the level of 2.5-3% up to 2060, which decreases steadily to the level of 1.4% by 2100. This growth rate is similar to the national projected growth rate. On the other hand, the other two surrounding regions (South East and East England) are projected to have higher growth rates, which are at the level of 3% up to 2060, and decreasing to 1.8% in 2100.

From a sectoral perspective, the Scale Intensive Information Networks category, including banking/finance, communications, professional, business and other services, are projected to become the most dominant category for all three regional economies. High growth rates are also projected for the Science Base Service Suppliers category, which becomes the second largest category beyond 2060 in GVA. Both of these categories are projected to require high productivity personnel, which explains the lower growth rate in employment. On the other hand, Supplier Dominated General and Scale Intensive General categories, which include traditional heavy industries, show low or negative growth rates with products from these sellers progressively substituted by imports. Furthermore, Scale Intensive Physical Networks

and Supplier Dominated Services categories, including transportation, education, hotels and public administration show a considerable increase in their output. Within the Supplier Dominated Services category a different evolution curve is projected in employment, as hotels, public administration and defence sectors have a significant decrease in projected jobs while health and to a lesser extent education, are projected to create new jobs. Finally, Scale Intensive General, Science Based General and Specialised Suppliers General categories are projected to have more moderate increases in growth rates, which are enough to allow them account for a small but almost constant percent of the total output and employment for the whole examined period to 2100.

What we found:

- Given an assumption of UK growth in GDP, London is projected to grow at roughly the same rate.
- The neighbouring regions (Southeast England and East England) are project to have higher growth rates.
- Ageing population and changing working habits are major influences on changing economic activity.
- Banking, finance, business and science-based industries are expected to grow most rapidly, with heavy industry diminishing.
- These economic changes need to be taken into account when planning for a low carbon economy and adapting to climate change.

17 Dewick, P., Green, K., Miozzo M., (2004). Technological change, industry structure and the environment. *Futures*, Vol. 36, pp. 267-293.

18 Dewick, P., Green, K., Fleetwood, T., Miozzo, M. (2006). Modelling creative destruction: Technological diffusion and industrial structure change to 2050. *Technological Forecasting & Social Change*, Vol. 73, pp. 1084-1106.

Projections of land use change in London in the 21st Century

What we did:

A Land Use Transport Model was developed to provide projections of the future population at a ward scale and for the London and the Thames Gateway. An Urban Development Model was developed to generate plausible high resolution projections of land use change on a 100 x 100 m grid. This hierarchical combination of models has been used to test the implications of different socio-economic scenarios and planning policies.

Changes in land use take place over extended timescales and when they have occurred can be very hard to reverse. We can expect that land use decisions made now will be reflected in land use patterns even in 2100. Many of today's buildings will still exist. Thus analysis of current land use and possible future land use changes provides a key to understanding possible futures for London. Land use is a determinant of vulnerability to risks such as flooding and the urban heat island. It also influence human mobility and thus emissions from commuting and other trips.

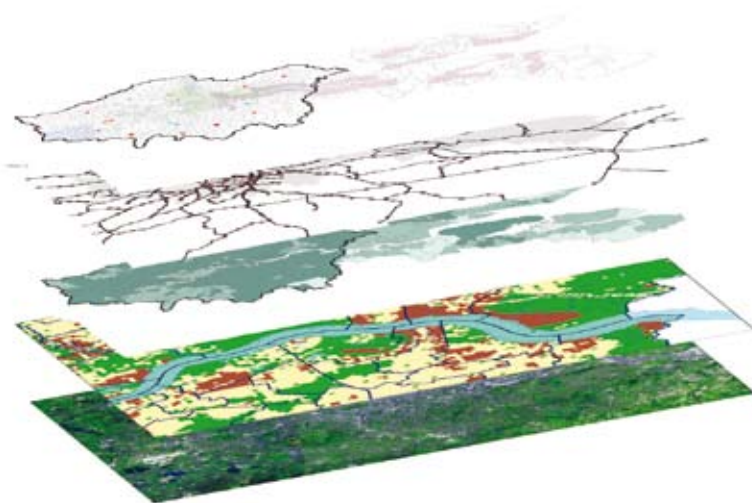
Land use changes take place as a consequence of complex socio-economic and political processes, many of which are not predictable. However, we know that future development is influenced by the availability of land. The accessibility to transport links and workplaces is one of the main determinants of the locations of residential development. Other residential development "attractors", such as local amenities, are also quite well understood and are reflected in house prices. These insights provide the basis for understanding and simulating processes of autonomous land use change under different scenarios of population and employment, and for analysing the effectiveness of land use planning policies and transport infrastructure development.

Characterising transport accessibility in terms of generalised cost

The cost of travel between home and work is a primary determinant of where people choose to live. In a city like London, travel to work can be undertaken by a number of different public or private transport modes. Four modes of travel are considered within the UIAF: road (private car), bus, train and light rail (London Underground, Docklands Light Railway or Tramlink).

Accessibility is measured in terms of Generalised Travel Cost, which accounts for all the time, monetary and perceived (e.g. overcrowding, safety) costs associated with travel. Maps of London's transport networks were constructed from publicly available data to ensure repeatability and transferability to other areas within the UK. Journey time is measured by creating network models of the various modes, within a Geographical Information System. These networks represent the actual transport networks within Greater London thus allowing, with data on routes and speeds, the time to travel between every ward in London to be calculated:

- The road network was constructed from Ordnance Survey's Integrated Transport Network (ITN) dataset. Local streets were removed to leave 65,000 links for the Greater London area. Travel speeds were assigned from the 2006 London Travel Report¹⁹ averages.
- Ordnance Survey Strategi data were used for the rail network. Speeds were computed from the timetables of specimen routes and applied as averages across the network.
- The light rail network was constructed from data provided by TfL. As with the rail network, average speeds were calculated and applied to the whole network.
- The bus network used the road network, whilst journey times were estimated using data supplied by Jacobs Consultancy that recorded timing points along bus routes.



Planning policy:
Attractors, constraints etc

Transport network and
generalised cost of travel

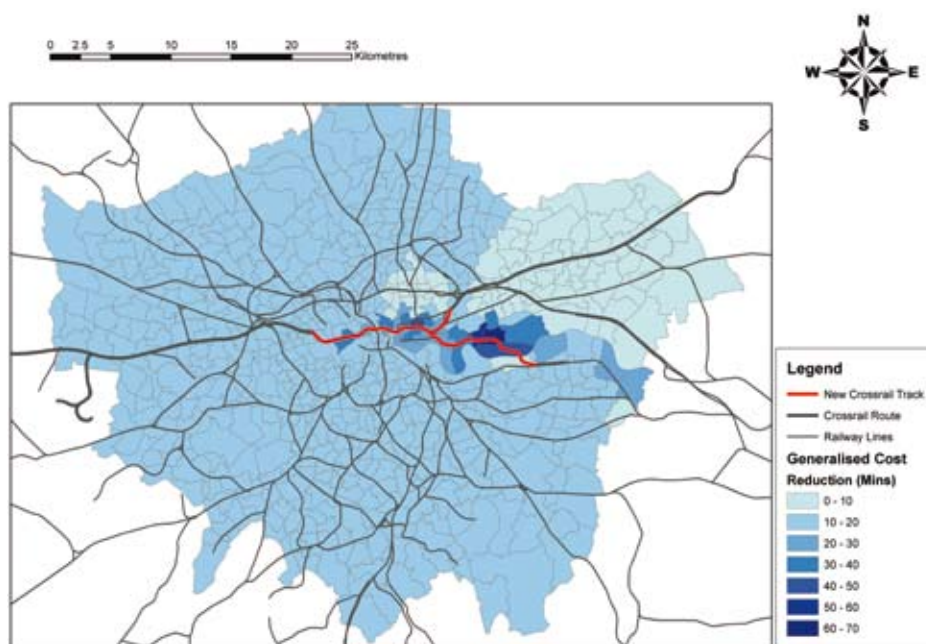
Spatial allocation of population
and employment

High resolution downscaling
of development

The real world

Overview of land use modelling components

¹⁹ <http://www.tfl.gov.uk/londontravelreport>



Map showing the reduction in Generalised Travel Cost from Heathrow to all other census wards within the GLA boundary by rail after the construction of Crossrail.

Network journey times are incorporated with other factors of Generalised Travel Cost, such as ticket fares, congestion charge, fuel consumption, waiting time and time taken to access the transport networks, to provide an indication of the overall cost of travel between every census ward.

Intangible costs, such as overcrowding and safety were taken from the Department for Transport's Transport Analysis Guidance²⁰. These costs are measured between the 801 wards in London and the Thames Gateway, giving

over 640,000 Generalised Travel Costs between origins and destinations for journeys to work. Future changes in connectivity resulting from proposed infrastructure investments. In particular, we studied the effects on Generalised Travel Costs of a range of infrastructure improvements being considered by Transport for London. The Generalised Travel Costs can also be modified to test the effect of assumed travel costs such as network speed, waiting time and fares.

Generalised Travel Cost (measured in minutes) for (i) a journey between Heathrow and St. James' Park and (ii) the average cost of travel between all census wards, for a range of different investment scenarios based on the TfL's Transport 2025 study²¹

		Road*		Rail		Light rail		Bus	
Basic	(i)		161.7	Crossrail High Speed 1 Heathrow Express to T5	115.9	T5 Extension		132.2	91.9
	(ii)		66.1		102.4			154.6	96.8
A	(i)	Thames Gateway Bridge	161.7	Reduce journey time (4.5%)	114.1	DLR Extensions Greenwich and East London Transit systems		132.1	Increase bus supply (20%) 90.6
	(ii)		65.7		100.6			150.2	95.5
B	(i)	Silvertown Link National road user charging	163.9	Crossrail 2 East London line extension	114.1	Reliability improvements Tramlink extensions West London & Cross river tram services DLR Extension to Dagenham Dock		132.1	Increase bus supply (40%) 82.3
	(ii)		67.6		99.5			145.8	87.71

* This includes the full congestion charge cost which equates to ~95 minutes Generalised Travel Cost

²⁰ <http://www.dft.gov.uk/webtag/>

²¹ Transport for London (TfL) (2006) Transport 2025 - Transport vision for a growing world city, TfL Group Transport Planning and Policy, London.

Land Use Transport Model (LUTM)

Scenarios of aggregate change in employment for London and the two neighbouring regions (East and Southeast) were output from the MDM-E3 economics model. The land use model provides spatially explicit estimates of change in population and employment in London and the Thames Gateway. It has been used to test the long term effects of planning policies (e.g. property density and greenbelt constraints or regeneration area incentives).

The LUTM calculates changes in population and employment for each census ward using a spatial interaction model. Different sectors of employment are distributed according to existing patterns modified by policy initiatives and planning constraints, whilst remaining consistent with the regional economic scenarios. Population change is calculated on the basis of the Generalised Travel Cost alongside other development drivers such as regeneration initiatives, whilst constrained by the availability of developable land.

The LUTM is first calibrated to the existing pattern of travel movements on each mode, constrained so that the observed transport modal split is replicated. The parameters obtained from the calibration are then used along with the future employment predictions to generate future population estimates for each London ward. Users are then able to test different employment scenarios, planning policy initiatives and changes in the modal split of future travel.

Factors driving land use change, by stimulating development in one area in preference to another are referred to as *attractors*, whilst *constraints* are factors that completely stop or reduce the attractiveness of development in a particular area.

Constraints that are incorporated in the LUTM

- Current development (from OS MasterMap): buildings, infrastructure, manmade areas
- Current water courses and lakes
- Environmental areas: SSSIs, Nature reserves, Greenbelt
- Constraints used in the London Plan: Metropolitan Open Land, Conservation Areas
- Floodplains (zones 2 (extreme flood extent) and 3)

Attractors that are incorporated in the LUTM

- Employment
- London Plan designations: Opportunity Areas, Metropolitan centres, Regeneration Areas, Areas for Intensification
- Proximity to current development
- Proximity to road network
- Proximity to public transport
- Proximity to amenity (parks, riverside)
- Previously-developed land (brownfield sites)
- Quality of schooling (measured from the Index of Multiple Deprivation)
- Thames Gateway Development zones
- 2012 Olympic Games site

The model is flexible so other spatial constraints or attractors could be readily incorporated. The transition to our four different land use 'paradigms' was simulated using a selection of these constraints and attractors and weighting their importance to achieve the desired land use objectives.



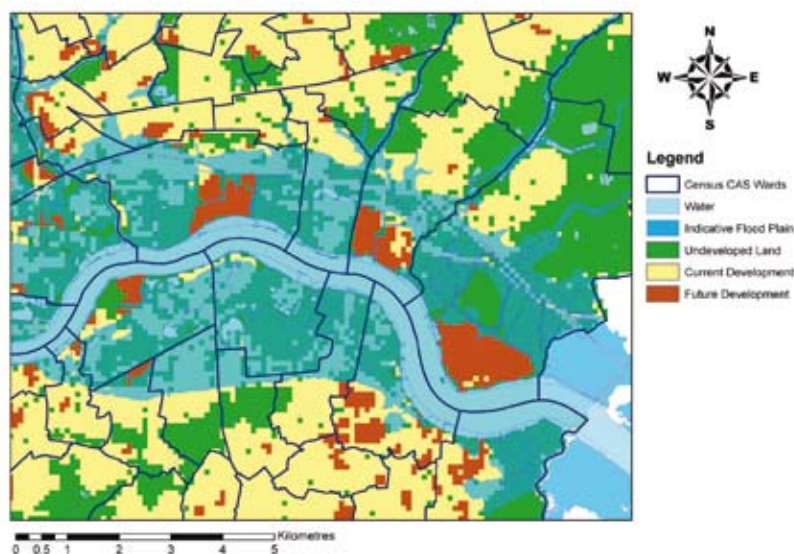
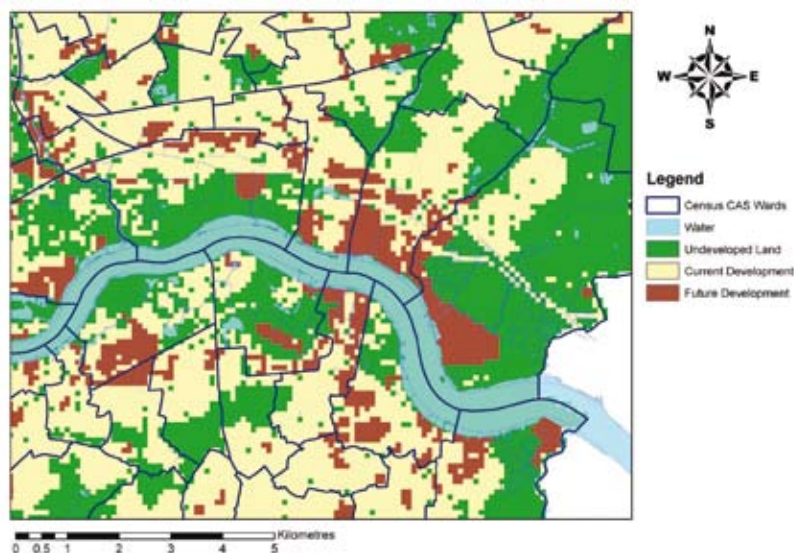
(i) Baseline
Population and employment tend towards existing settlements.
Transport infrastructure remains the same, with capacity increasing in response to demand only to ensure existing trends are unhindered by capacity constraints.



Maps of population by ward for today (centre) and 2100 where clockwise from top left four maps show different development paradigms Baseline (maintaining current trends), Eastern, Centralisation and Suburbanisation

Outputs from the LUTM for four different land use paradigms (or sets of planning policy packages) have been developed. These land use paradigms have been constructed specifically to explore the implications of contrasting development trajectories. In using the LUTM to simulate these alternative 21st Century land use paradigms we have found that individual policies are insufficient to steer land use away from the base line and towards any noticeable spatial pattern of development. A package of policies including infrastructure development, planning incentives and constraints are required to shape land use change in London.

Land use in East London on a 100 x 100m grid showing existing and future developments (i) under the baseline land use paradigm (ii) under conditions where a policy to reduce exposure to flood risk has led to the banning of future floodplain development.



High resolution Urban Development Model (UDM)

Analysis of population and employment at the ward scale using the LUTM is suitable for many purposes. This also is the resolution at which much of the calibration data needed for the LUTM is collected, so is a sensible scale from a modelling point of view is collected. However, for the purposes of some climate change impact assessments a higher resolution model is necessary. An Urban Development Model (UDM) that operates at the sub-ward scale has been built to achieve this. The model determines the most probable new development locations and then allocates them new residential development of particular densities in order to satisfy the predicted change in population for the ward. For consistency, the same spatial attractors and constraints used in the LUTM are also employed in the UDM. At every location within a ward the proximity of, for example, a rail station or school can be measured exactly. In the results shown in the maps below we illustrate how a river might act as an attractor (for river views, or industrial activity) or a constraint (to avoid exposure to flooding). The results show the possible effect on the layout of buildings and other land uses, on a 100 x 100m grid.

What we found:

- Not accounting for the space required by any additional industry and services, approximately 2.3million more people could be accommodated within the Greater London boundary assuming no changes in development density.
- Four land use policy packages have been constructed to test four different land use paradigms for London and the Thames Estuary.
- Transport connectivity is an important mediator of land use, but to stimulate strong growth in the East of London or to decentralise London requires use of additional policy incentives and constraints.
- Nearly 40% of land that has not been developed within the Greater London boundary is greenfield, whilst approximately 8% of undeveloped land is in the floodplain. If no green land is freed up, and population density in each census ward remains the same tradeoffs between exposure to flooding, amount of green space and living density will be necessary.

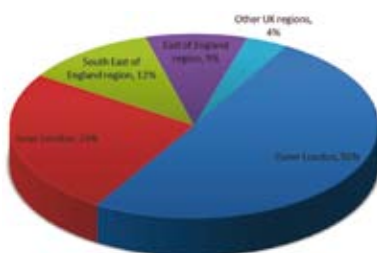
Carbon dioxide emissions from personal transport

What we did:

The achievability of significant carbon dioxide emissions reductions from personal land-based transport in London was analysed using data on existing transport behaviour, our demographic and socio-economic scenarios and a range of policy options for carbon emissions reductions from transport.

A profile of carbon dioxide emissions from personal land-based transport modes was derived using Great Britain National Travel Survey²² (NTS) data and carbon emissions factors (the emissions per journey kilometre) for different modes. Given the number of journeys that start or finish outside London these had to be apportioned appropriately. The emissions were then aggregated for all London and regions outside London using Census of Population data. The total emission for 2005 from personal transport with origin and/or destination inside London was 4.9 Mt CO₂/year. Analysis of the proportion of total carbon dioxide emitted within London during the baseline year (2005) according to the emitters' area of residence shows that outer London residents are responsible for over half of London's transport emissions and inner Londoners for a quarter.

Carbon dioxide emissions from personal transport by residential location



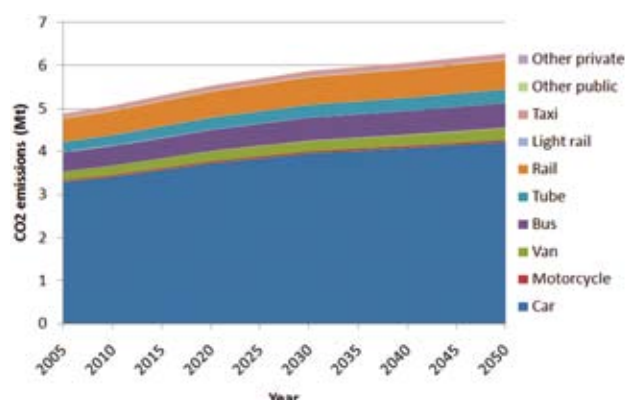
A baseline of carbon dioxide emissions, based on equal per capita consumption according to different transport modes, was projected to 2050 using estimates of future population. If no action is taken to reduce carbon

Estimated mode share (% trips) in 2025 and 2050 for policy option and percentage change in cumulative CO₂ emissions from 2005 baseline

		2005 ²⁴	Option 1: 2007 Climate Change Action Plan (CCAP)		Option 2: Technology		Option 3: Technology & carbon trading		Option 4: Technology, carbon trading, modal shift	
		2005	2025	2050	2025	2050	2025	2050	2025	2050
Modal split	Car/van	41	32	30	32	30	28	21	25	5
	Public transport	37	41	43	41	43	43	45	34	35
	Walk	20	22	22	22	22	23	24	25	26
	Cycle	2	5	5	5	5	6	10	16	34
Percentage change in emissions	CCAP		-12%	+3% *						
	IEA				-21%	-47%	-24%	-55%	-36%	-76%
	King				-24%	-67%	-27%	-86%	-38%	-92%

* The CCAP only sets out policy until 2025. If no further measures are implemented rising demand will counteract any earlier gains in emissions reduction.

emissions from personal transport population increase alone will result in an increase in emissions of 2.1Mt CO₂/year by 2050.



Carbon dioxide emission projections 2005-2050 for baseline according to different transport modes

Development of policy packages for reduction of emissions from personal transport

In order to estimate the impact of different policies to reduce CO₂ emissions in London, four policy packages were developed and compared with the baseline projected increase. A number of assumptions were made regarding mode share in each package.

Option 1: Implementation of the London Mayor's Climate Change Action Plan (CCAP)²³.

Option 2: Additional savings from potential technological advances.

Option 3: Technological advances and increased demand for zero carbon modes of transport incentivised by carbon trading.

Option 4: Substantial modal shift to walking and cycling, supported by appropriate changes to London's transport infrastructure to facilitate their uptake.

²² <http://www.dft.gov.uk/pgr/statistics/datatablespublications/personal/mainresults/nts2006/>

²³ GLA (2007). The London Mayor's Climate Change Action Plan, Greater London Authority, February 2007.

²⁴ TfL (2005). The London travel report 2005. Transport for London.

The emissions projections calculated here suggest that the CCAP alone will not achieve the magnitude of savings sought by policy makers in the context of DECC's Low Carbon Transition Plan²⁴. The CCAP recognises that to achieve the maximum possible emissions cuts would require central government action as well as London-led action. The improvements in technology tested in Options 2, 3 and 4 were based on an assumed 80% decrease in greenhouse gas emissions per kilometre travelled by 2050²⁵. The sensitivity of the emissions model was tested by comparing these assumptions against the International Energy Agency's²⁶ less optimistic estimates of a 50% reduction in the same timeframe.

The rate of uptake of more efficient forms of transport differentiates Options 2 and 3. Whilst replacement rates of existing vehicles to high efficiency petrol cars is approximately the same, carbon trading with aggressive periodic cuts in quota drives investment in low emissions public transport, particularly rail so that for Option 3, 90% of all rail journeys are powered by zero carbon energy by 2050 - double that assumed in Option 2. Moreover, it acts as a strong motivator to drive consumer demand for low and zero carbon technology, which in turn reduces production costs and encourages further uptake – with over 40% of personal cars being zero carbon by 2050 under Option 3.

For options 3 and 4, differences in mode share are solely responsible for the difference in carbon reductions. Option 4 envisages major lifestyle shift for Londoners so that walking, cycling and public transport become the norm for most trips. Clearly such a scale of change would require a change in attitudes (e.g. acceptance of home working) and localisation of many activities (e.g. services, jobs) and associated land-use and infrastructure changes.

Technology combined with the CCAP under maximum improvements in vehicle efficiency and uptake could achieve dramatic reductions. However, this is unlikely to be attainable in practice without a strong motivator to drive consumer demand for low and zero carbon technology, which in turn reduces production costs and encourages further uptake. To maximise emissions cuts by as much as 92% would require changes in behaviour, which would in part need to be supported by infrastructure and land use changes. Whilst technology clearly has an important role to play in achieving an 80% carbon reduction, the possibility of stimulating lifestyle changes through the implementation of measures such as a carbon trading scheme has additional benefits that would not necessarily be delivered through technology alone. Whilst the quantitative measurement of such benefits is beyond the scope of the current research, there could be, for example, improvement through increased walking and/or cycling to health and wellbeing. In addition, in terms of costs to society, an increase in physical activity and a consequent reduction in traffic congestion and improvement in air quality could result respectively in reduced costs to the National Health Service and the economy in general.

What we found:

- Carbon dioxide emissions from personal land transport in London are currently 4.9Mt CO₂/year and will rise to 6.3Mt CO₂/year by 2050 if no mitigation action is taken, assuming per capita transport use remains the same.
- Analysis shows that the average Outer London resident contributes approximately twice the carbon dioxide emissions from their personal transport as the average Inner London resident. People living in the neighbouring regions contribute significantly to London's transport emissions.
- The baseline was compared with several scenarios including the London Climate Change Action Plan (CCAP). The CCAP shows that small reductions are possible (~10%) over its timeframe (until 2025) but after that increased demand will offset these gains.
- Additional reductions require a portfolio of measures including uptake of low-carbon vehicles (e.g. plug-in electric or hydrogen fuel cell from renewables), carbon trading and increased modal switching to walking and cycling. The majority of these measures are required if personal transport is to help reduce the UK's overall emissions by 80% by 2050. To implement these changes requires substantial changes in infrastructure, lifestyles and behaviour.



24 HM Government (2009). The UK Low Carbon Transition Plan: National strategy for climate and energy, London, The Stationary Office, London.

25 King, J (2008). The King review of low-carbon cars. Part I: the potential for CO₂ reduction. Prepared for HM Treasury. The Stationary Office, London.

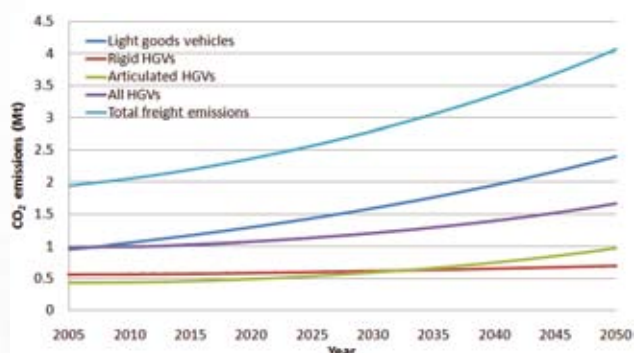
26 International Energy Agency (2008). Energy technology perspectives 2008: scenarios and strategies to 2050. Organisation of Economic Cooperation and Development.

Carbon dioxide emissions from freight transport

What we did:

Trends in freight transport in London and carbon dioxide emissions have been analysed. Policy interventions that might reduce these emissions have been tested.

Analysis of carbon dioxide emissions from freight in London is constrained by the availability of historical data. The source approach which allocates emissions on the basis of vehicle kilometres within the Greater London area was adopted. Traffic data²⁸ were combined with fleet composition and emissions factors data²⁹ within a simple spreadsheet-based model to provide a baseline profile of traffic and emissions based on the available historical information, which was limited to the period 1996 to 2005. This historic trend was extrapolated to provide baseline projections for traffic growth and emissions to 2050. Growth in the largest Heavy Good Vehicles (HGV) of 6 and more axles was capped given the very high recent growth rates. The resulting emissions trends were found to be within 1 to 2% of baseline projections contained in both the London Atmospheric Emission Inventory (for 2010)¹⁷ and the London Freight Plan (for 2025)³⁰. These provided a good baseline from which to explore policy interventions.



Baseline projections of carbon dioxide emissions from freight transport in London by vehicle type

Evidence of actual and potential impacts of transport policies and developments within the freight and logistics sectors on traffic levels and emissions were reviewed. This evidence base was used to develop assumptions for the potential carbon dioxide emission reductions from a range of single policy instruments. By 2050 it was assumed that 60% of light goods vehicle (LGV) kilometres would be operated by zero emission vehicles, 30% by low emission vehicles (defined as offering 20% lower emissions than current) and the remaining 10% would still be emitting close to current levels. 75% of heavy goods vehicle kilometres were assumed to be low emission by 2050 with the remainder emitting close to current levels. Emission savings per vehicle kilometre

from drivers' training were taken as 10% and applied to all HGV traffic and 75% of LGV traffic by 2050. Construction Consolidation Centres providing centralised depots for construction materials were assumed to generate savings of 50% in traffic volume and apply to 25% of total HGV traffic in 2050. Urban Distribution Centres to centralise delivery activity and Vehicle Reception Points, which facilitate parking and delivery, were assumed to be capable of generating savings in delivery vehicle kilometres of 25% and 15% respectively, and apply to up to 15% and 25% of total HGV and LGV traffic by 2050. Finally, the relaxation of delivery time restrictions were assumed to be able to generate savings of about 15% in vehicle kilometres and apply to up to 30% of freight traffic in 2050.

The impacts of the policy instruments are not additive, indeed, it is clear that greater improvement in vehicle efficiency will reduce the potential savings offered by measures that improve driving practices or reduce total vehicle kilometres. Nevertheless if all the suggested measures were adopted it might be possible to achieve savings of around 25% in 2025 and 50% by 2050 compared to the baseline. These projections may be compared with those in the London Freight Plan³¹ and are broadly consistent, with variations that might be expected given the different aims and constraints on the two studies. Consultation with a small number of experts suggests a lack of consensus on the level of savings to be expected, but some agreement that low emission vehicles have the greatest potential.

28 TFL (2008). London Freight Data Report. London, Transport for London and University of Westminster.

29 We used the AEA (2007). National Atmospheric Emission Inventory. Available at www.naei.org.uk. Modified emission factors are now available in Boulter et al, (2009 – Emission Factors 2009: Final Summary Report. TRL and DfT, London) but not yet formally adopted. The application of these new factors to our model did not significantly modify the results of our policy tests.

30 TFL (2008). London Freight Plan - sustainable freight distribution: a plan for London. London, Transport for London.

31 Transport for London (2008). London Freight Plan: sustainable freight distribution: a plan for London.

Potential CO₂ emission reductions from a range of single policy instruments

Policy	CO ₂ emissions 2025 (Mt)	% change from baseline	% change from 2005	CO ₂ emissions 2050 (Mt)	% change from baseline	% change from 2005
Baseline	2.6		32.2	4.1		109.4
Promotion of Low Emissions Vehicles	2.1	-16.5	10.4	2.2	-45.1	14.9
Drivers' Training and Performance Measures	2.3	-9.6	19.5	3.5	-13.5	81.2
Construction Consolidation Centres	2.4	-5.4	25.1	3.5	-14.3	79.5
Urban Distribution Centres	2.5	-3.6	27.5	3.7	-10.1	88.2
Vehicle Reception Points	2.5	-1.0	30.9	3.9	-3.5	102.0
Relaxing Delivery Times (out of hours)	2.5	-2.3	29.3	3.8	-6.6	95.5

What we found:

- In the absence of further policy interventions, carbon dioxide emissions from freight may double by 2050.
- Our analysis suggests that, even with optimistic assumptions, single policy interventions cannot deliver any absolute reduction in emissions from 2005 levels, only slows their growth.
- The most effective single measure would be the diffusion of low and no carbon vehicles into the fleet. However, reliance on technical developments to deliver emissions savings is risky as zero carbon vehicles would be dependent on a larger and decarbonised energy sector.
- Even if zero or low emission vehicles achieve significant fleet penetration by 2050, emissions are likely to increase in the presence of current trends in freight traffic growth.
- Interventions that influence the number of freight trips are therefore critical to the success of carbon reduction measures in the freight sector. This will require very high levels of cooperation between planners and freight operators.

Carbon dioxide emissions from energy use

What we did:

A range of different policy options for energy demand reduction, technology change and energy generation were analysed.

Cities create greenhouse gas (GHG) emissions due to a variety of activities which take place within their boundaries. These activities may be considered as 'emissions sources'. These are considered in two forms: direct and indirect. Direct GHG emissions sources within a city may include energy that is combusted, treatment and disposal of degradable waste, existing industry sources, fuel extraction and processing. Indirect emissions may include the emissions associated with the manufacture (elsewhere) of the goods and services that a region consumes, electricity that is generated elsewhere (but consumed in the city/region), and extraction of raw materials (elsewhere). An emissions inventory allows these emissions to be presented together. An emissions inventory usually consists of either direct, or a combination of both indirect and direct emission sources.

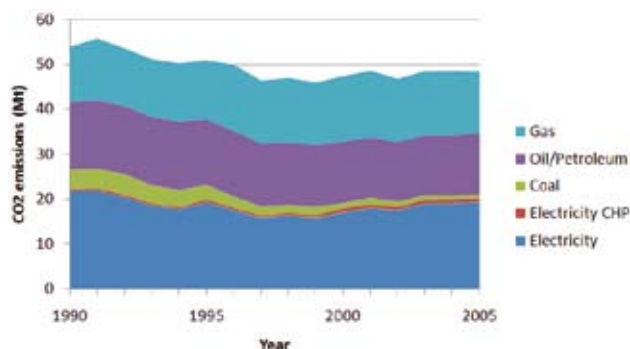
An emissions inventory enables policy makers to assess historical or current emission levels within a city. This then allows emissions to be compared over time. Assessment of the impact of previous policies on emissions levels will help it inform future policy decisions. In addition, an inventory provides a baseline upon which future emissions reduction targets are based and, against which policy options may be tested.

Within this research programme an online inventory tool has been produced that enables policy makers to form their own GHG inventory. The methodology behind the tool has its roots in the Greenhouse gas Regional Inventory Protocol (GRIP)³². The methodology is largely based on direct emissions, with the exception of electricity, heat and waste. Emissions associated with generation of electricity and heat are allocated to the consumer, whereas emissions associated with the disposal of waste are allocated to the producer. The outputs can be presented in a number of ways, for example, emissions per capita, emissions per unit of GVA (in region and nation) and % of national emissions. The tool enables policy makers to determine what the relative contributions to emissions changes are created by changes in energy demand, fuel mixes and generation technologies, both by sector and overall.

When applying the inventory to the GLA for 1990-2005, carbon dioxide emissions have been presented by source. When applying the inventory to the GLA for 1990-2005, carbon dioxide emissions have been presented by source using energy consumption data. There has been a 1.5 Mt reduction in emissions from oil and petroleum. The greatest reductions in emissions are from electricity and coal having decreased by 2.5 Mt CO₂/year and 3.6 Mt CO₂/year respectively, despite an increase in electricity consumption. This is due to a drop in the carbon intensity of electricity production and an increase in gas usage over other fuels (gas emissions have risen by 1.7 Mt CO₂/year), as well as a decline in industry over this period.

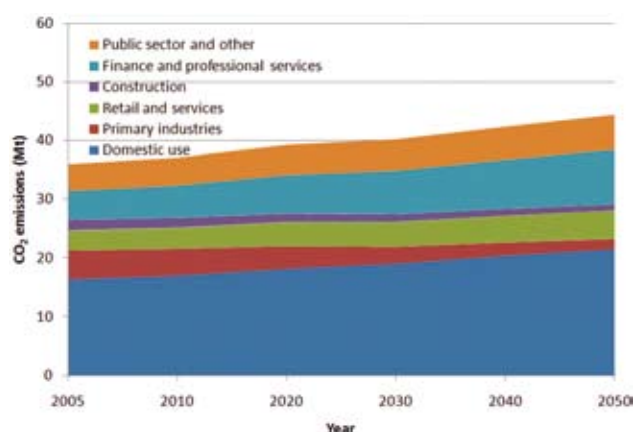
Data used in emissions inventory:

DTi Energy Inventory
ONS Regional Trends
Digest of United Kingdom Energy Statistics
UK UNFCCC National Inventory submission
DECC Regional Energy Statistics
Combined heat and power usage
On-site renewable energy database
Population
Building stock
Electricity supply portfolio
Non-electricity supply portfolio
Emissions reduction technology



Emissions inventory for Greater London 1990-2005 according to fuel source (includes household, industry, agriculture, commercial, transport emissions).

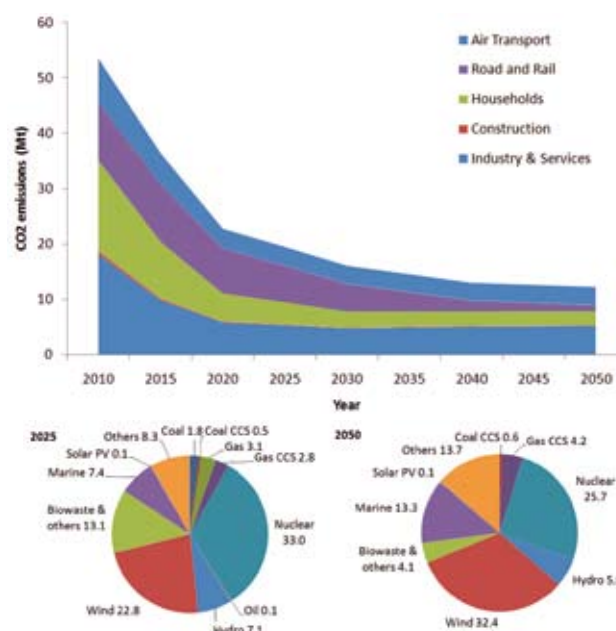
Emissions from energy use in London for different economic sectors (not including transport) and the domestic sector (assuming a high population growth projection) are projected to 2050. This baseline projection assumes energy demand per capita and/or unit of economic activity remains constant and there are no changes to energy generation mix and efficiency. Rising domestic, financial, retail and other emissions are a result of increases in population and employment in those sectors, whilst primary and construction emissions correspondingly decrease.



Emissions from energy use in London for different economic sectors (not including transport) and the domestic sector (assuming a high population growth projection).

Achieving carbon dioxide emissions reductions

We analysed the emissions reductions from different sectors and electricity generation by different technology types that are necessary to achieve a specified carbon dioxide emissions reduction (e.g. 60% or 80%). A range of intervention options have been considered as parts of portfolios of mitigation strategies. These options include policy measures, technological advancement, infrastructure change and behavioural change. For example, higher prices of carbon in trading systems; decentralisation of energy distribution networks and on-site generation; carbon permit revenue recycling to investments in energy efficiency in households. This latter option may provide incentives for improving the energy efficiency of domestic dwellings and appliances and for introducing new ones such as low-emission dwellings and solar appliances. Decentralisation of energy networks can substantially reduce transmission and distribution losses and can make use of small scale on-site renewable energy sources. Moreover, installation of combined heat and power (CHP), or tri-generation, plants makes use of heat energy that might otherwise be lost, further increasing efficiency. Large emissions reductions could be achieved by altering the national grid generation, but whilst decentralisation and CHP may require changes to infrastructure, and possibly even new energy governance structures, they can deliver substantial benefits.



How to achieve 80% reduction in CO₂ emissions; sector contributions (graph) and technology mix (piecharts). In this package of mitigation measures, no demand management is assumed, giving an indication of the radical and rapid shift in energy generation mix required to sustain our current per capita energy demands.

What we found:

- GHG emissions in London are expected to increase by more than 20% by 2050 if per capita consumption remains the same.
- Decarbonisation of the national grid using existing (e.g. nuclear or wind) or emerging (e.g. carbon capture and storage) technologies, building retrofitting to improve energy efficiency or alternatively the decentralisation of energy generation and mass deployment of Combined Heat and Power networks within London all represent substantial infrastructure changes. Due to the lead time to make these types of changes, immediate action is required if ambitious greenhouse gas emissions cuts are to be achieved.
- A mixture of policy measures to reduce demand and technological measures will be most effective at achieving the 80% cuts sought by DECC's Low Carbon Transition Plan³³.
- Mitigation policies in London are unlikely to be able to achieve ambitious cuts without supporting national government action.

³³ HM Government (2009). The UK Low Carbon Transition Plan: National strategy for climate and energy, London, The Stationery Office, London.

Impacts of climate change on urban temperatures

What we did:

A new version of the Met Office Hadley Centre's regional climate model that includes the effects of land surface and anthropogenic heat emissions was coupled with a weather generator to analyse temperature in London under current and future conditions. The number of vulnerable people exposed to heatwave in these future scenarios events was analysed.

Increased temperature can lead to heat stroke, physiological disruption, organ damage, and even death. The 2003 heatwave in Europe resulted in the death of over 2,000 people in England and Wales, and the impact was greatest in London where deaths of people aged over 75 increased by 59%³⁴.

Temperatures in cities are higher than the surrounding areas because of effects of buildings and paved areas on heating and cooling and because of the large amounts of waste heat released in cities, from heating and cooling of buildings, traffic, and even human metabolism. This amplification of urban temperatures relative to surrounding countryside is referred to as the 'urban heat island'. The urban heat island intensity, the difference in temperature between the inner city and a rural reference point, is usually at a maximum between 11pm-3am. The heat island in London has, on average, become more intense having been measured as $\sim 2^{\circ}\text{C}$ ³⁵ almost two hundred years ago, $4\text{--}6^{\circ}\text{C}$ forty years ago³⁶ and has increased, on average, at a rate of $0.12^{\circ}\text{C}/\text{decade}$ ³⁷. London's urban heat island has been measured as high as 9°C in a recent extreme event³⁸.

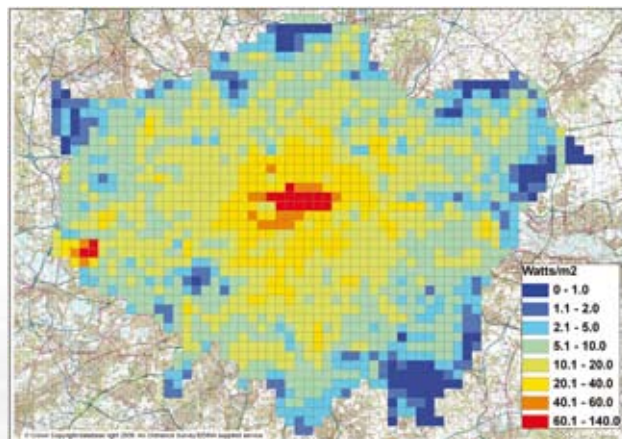
New projections of urban temperatures for London

Urban temperatures are set to increase due to climate change. In order to predict this effect, it is necessary to model how the urban heat island will respond to a changing climate. Even the highest resolution regional climate models tend to be at a scale larger than required to explicitly represent urban heat islands, and such models cannot practically be run for extended periods of time. However urban parametrizations suitable for inclusion in climate models are becoming more widely available. In our

research the Met Office used a "tiled" MOSES2 surface scheme within a regional climate model to allow for sub-grid scale variations at the land surface. Each model grid box is composed of a varying mix of five vegetation types, and four non-vegetation surfaces that includes urban. The transport of heat and water between the atmosphere and surface is calculated for each surface type within the grid cell. The scheme allows for surface and air temperatures to be diagnosed individually for each surface type.

The Met Office Hadley Centre regional climate model (RCM) was used to downscale climate change projections from the Hadley Centre general circulation model (HadCM3). For these RCM experiments a projection from the medium emissions (SRES A1B) transient climate change scenario from the HadCM3 model were used as boundary conditions to drive the RCM for the years 1971-1990 and 2041-2060.

Energy use statistics for London have been analysed to estimate the emissions of heat into the urban atmosphere³⁹. The results suggest heat fluxes averaged over a 25km grid cell located over the city centre of London to be of order $25\text{W}/\text{m}^2$, and for urban areas not including the core to be of order $15\text{W}/\text{m}^2$. We have used the more conservative value of $15\text{W}/\text{m}^2$ as a default heat flux estimate at the RCM resolution, but have conducted a set of sensitivity tests with the heat flux at $0\text{W}/\text{m}^2$, $15\text{W}/\text{m}^2$ and $45\text{W}/\text{m}^2$. This heat flux is included in the model as an additional source to the surface energy balance equation of the urban tile.



Average anthropogenic heat emissions from London

34 Johnson, H., Kovats, R. S., McGregor, G., Stedman, J., Gibbs, M. and Walton H. (2005). The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates, *Eurosurveillance*, 10(7-9): 168-171.

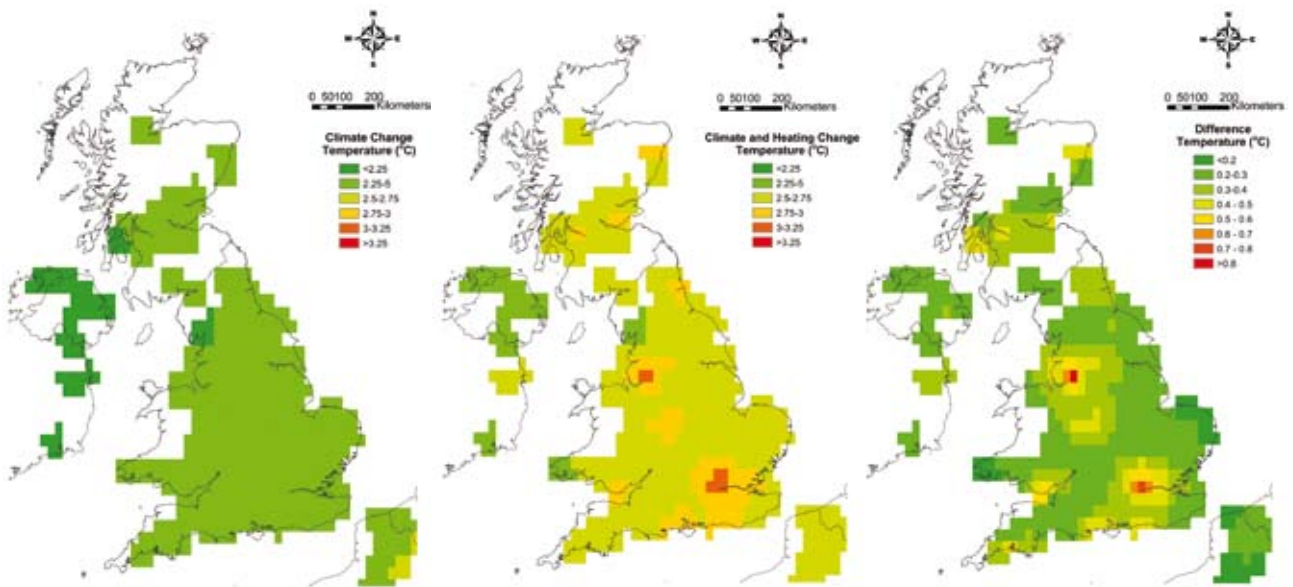
35 Howard, L. (1820). *The Climate of London*. W. Phillips, London.

36 Chandler, T. J. (1965). *The Climate of London*. Hutchinson & Co., London.

37 Wilby, R. L. (2003). Past and projected trends in London's urban heat island. *Weather*, 58(7): 251-260.

38 GLA (2006). *The London Atmospheric Emissions Inventory 2003*. Greater London Authority, London (www.london.gov.uk).

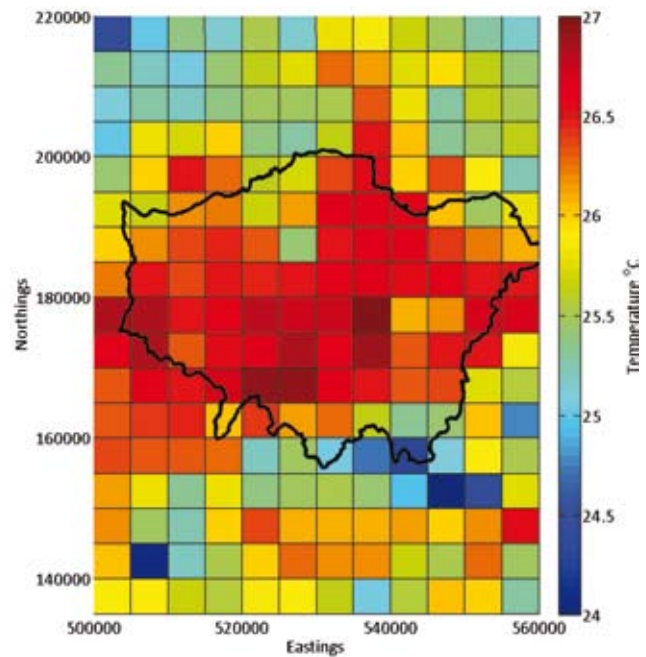
39 Greater London Authority (2006). *London Energy and CO₂ Inventory (LECI) 2003*. Greater London Authority, London.



The mean change in temperature from present to 2050s under the medium UKCP09 scenario for (i) climate change only, (ii) climate change and increased heat in urban areas and (iii) the difference map that show how increased energy use in cities and consequent heat emissions will amplify the urban temperature.

The occurrence of hot nights and air frosts is projected to change markedly in a changing climate. The most dramatic results are found when both climate change and the urban heat island are taken into account. This is particularly true for the situation of increased anthropogenic heating. Tripling the anthropogenic heating rate has a greater influence in the 2050s climate than for present day in these simulations. Most notably there is an increase in minimum night time temperature of approximately 0.5°C which could further increase the risk to people during a heat wave as it will be harder for bodies to cool down overnight. Sensitivity of urban climate to anthropogenic heat release is dependent not only on the magnitude of the heating and size of the city, but also on the local climate.

A stochastic weather generator similar to the one developed for UKCP09 was used to produce daily and hourly output for 5 km grid boxes over London and surrounding area. The weather generator was calibrated against the Met Office gridded temperature dataset. Future scenarios of temperature were generated by applying the changes in temperatures from the Met Office Hadley Centre model described above.



Projected mean summer (June, July, August) maximum daily temperature in London for the 2041-2060.

There are a number of definitions for a heat wave, but here we use the Met Office temperature threshold definition, which for London is two consecutive days where the maximum day time temperature exceeds 32°C and the minimum night time temperature in between exceeds 18°C .

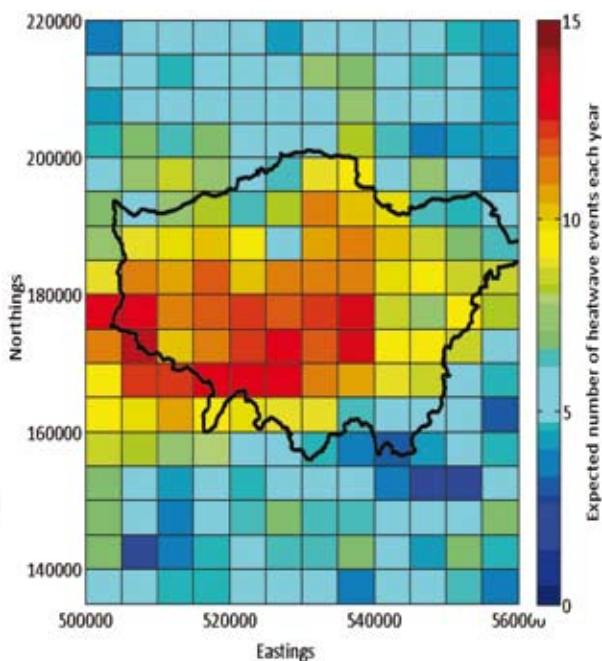
Spatial planning has an important role to play in mediating the risk of heat waves. The heat wave risk is here defined as the expected annual number of heat wave events (exceeding the Met Office temperature threshold) multiplied by the number of most vulnerable people (0-4 and >65 year olds) exposed to the event. Whilst we have not been able to analyse how changes to the built environment alter temperature patterns, we have analysed the effect of changing population distribution on vulnerability to heat waves associated with our four land use paradigms. By 2050 for each land use paradigm heat wave risk will increase by a factor of:

- Baseline: 3050
- Eastern axis: 2800
- Centralisation: 3140
- Suburbanisation: 3190

However, this analysis does not consider the scope for physiological adaptation to the warmer climate - already London has a higher temperature threshold for a heat wave compared to other UK regions. Conversely, the benefits in terms of reduced risk from cold related illness and mortality, as a result of rising minimum winter temperatures, could outweigh the impacts of heat wave risk.

What we found:

- By the 2050s, one third of London's summer may exceed the Met Office current heat wave temperature threshold.
- Land use planning has a notable effect on the number of people exposed to heat waves, but is much less important than the change in climate.
- A threefold increase in anthropogenic heat emissions (e.g. from air conditioning) on top of climate change has a negligible impact on maximum day time temperature, but raises minimum night time temperatures by 0.5°C which will aggravate heat stress.
- A warmer climate will bring benefits in terms of reduced exposure to extreme cold events in winter.



Map of expected number of events in a year that exceed the Met Office heatwave threshold of two consecutive days where the maximum day time temperature exceeds 32°C and the minimum intervening night time temperature exceeds 18°C for the 2050s in the UKCP09 Medium scenario.

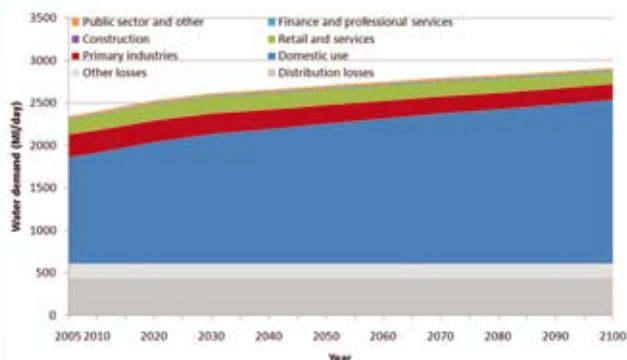
Impacts of climate change on water availability

What we did:

Simulations of rainfall, under current and future climates, were combined with a hydrological model and a water resource model to analyse present and future flows and water resources available to London. Scenarios of demand and future management of the resources were used to evaluate the risk of droughts in the London Water Resource Zone.

Compared to the rest of the UK, London is more vulnerable to changes in the surface water regime, which provides about 80% of the city's water, compared to a UK average of 30%. London's annual rainfall is two thirds the average for England and Wales. If precipitation reduced in future it will lower the available volume of surface water. Population growth will place further strain on water resources, and a warmer climate may have a positive feedback increasing household demand. Furthermore, higher summer temperatures and lower rainfall may reduce soil moisture and groundwater replenishment which may not be fully compensated by increases in winter rainfall.

The economic and population scenarios described previously were used to estimate how domestic and industrial water demand in various sectors may change in the future. In the baseline demand scenario per capita consumption remains constant at approximately 160 litres/person/day. There is a general increase in overall demand, driven predominantly by rising population, although this rise is tempered partially by the projected reduction in primary industries.

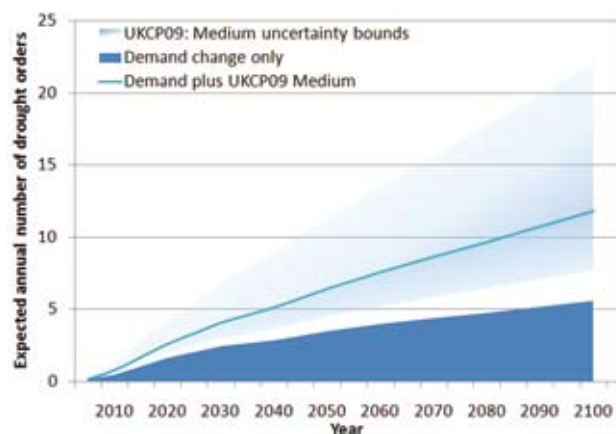


Projected changes in domestic and industrial water demand, as a consequence of increasing population and changing size of industrial sectors. This projection assumes no change in per capita demand.

The water resources system was analysed using a dynamic water resource system model that simulates water demand, abstraction, supply and storage capacity in the Lower Thames region (which incorporates the river Thames and its tributary the river Lee). Operating rules for reservoirs, bulk transfer agreements, groundwater and surface water abstractions and target river flows were parameterised according to the Lower Thames Operating Agreement and Thames Water's Water Resource Management Plan. While obeying these rules the water resource model attempts to meet supply from the available river flow, aquifers and reservoirs.

To analyse the effect of climate change, one hundred time series of 100 years of rainfall data were sampled from the UKCP09 weather generator and passed through the CATCHMOD rainfall-runoff model to establish as many time series of river flow in the Thames and Lee. This method illustrates how the new UKCP09 projections can be sampled in order to generate an impression of uncertainty in impacts variables (in this case river flows).

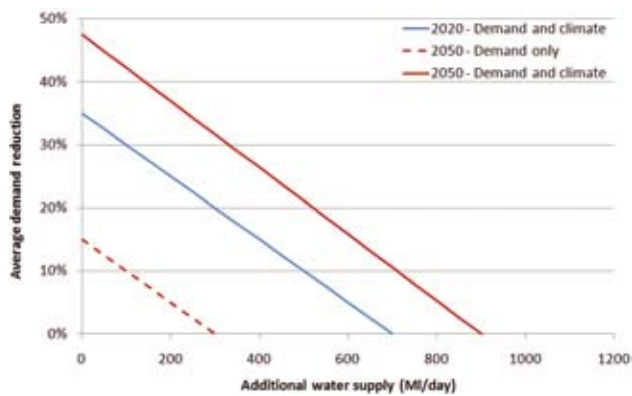
The frequency with which emergency drought orders (i.e. requiring deployment of standpipes, rota cuts and/or water tanks) would be necessary was recorded by the water resource system model under current and future conditions. Results for the demand only projection (i.e. no climate change) show that socio-economic change is a significant driver of water resource vulnerability. However, under the UKCP09 medium scenario, vulnerability increases further still.



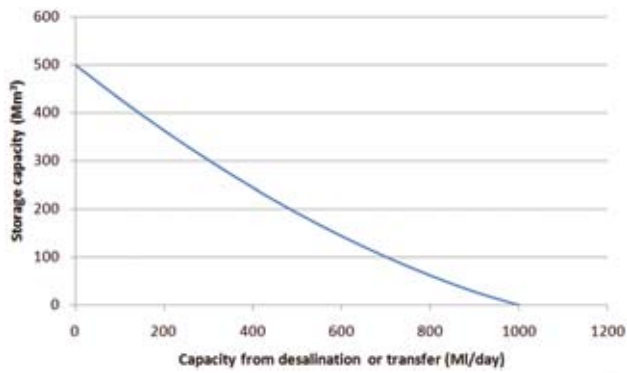
Expected annual number of drought orders under changing (i) demand only (ii) demand and UKCP09 Medium climate change scenario

London's current water resource system comprises a number of reservoirs capable of storing 300million m³ water. Against the baseline projections of demand and under the UKCP09 medium climate scenario a range of options that act to reduce demand or increase supply were tested.

Rather than highlight a few specific adaptation options, we show the necessary combination of demand and supply changes required to maintain the existing standard of service. Demand reductions are measured relative to the current average demand of individuals and the industrial and commercial sectors as well as leakage. Supply capacity could be increased through construction of storage reservoirs, facilities for direct reuse of waste water, desalination plants or inter-basin transfers. Assuming that no demand management measures are implemented, supply capacity could be increased through a mixture of reservoir storage and water reuse/desalination/inter-basin transfers to maintain the current standard of service.



The reduction in water demand (in terms of per capita consumption, industrial use and leakage) or additional supply required to maintain the present day level of service (in terms of expected annual number of drought orders) in (i) 2020 accounting for demand and climate change, (ii) 2050 accounting for demand change only and (iii) 2050 accounting for demand and climate change.



The required volume of reservoir storage needed to supplement a daily direct reuse, inter-basin water transfer or desalination capacity under the UKCP09 medium climate scenario and no demand reduction in the 2050s in order to maintain present day level of service.

The water resource systems consume large quantities of energy, and some adaptation options will be energy intensive involving desalination or pumping over long distances or significant vertical elevations. Depending upon the fuel mix for electricity supply, these adaptations may exacerbate emissions. For a 1000 MI/day desalination plant, and assuming the plant was powered from London's existing energy supply portfolio, with an operating efficiency of 2kWh/m³ the carbon dioxide emissions would exceed 1.7Mt CO₂/year. However, where demand management reduces the use of heated water there is the potential for reduced domestic energy consumption and the associated reduction in carbon emissions.

What we found:

- London's water supply is vulnerable to changes in river flows. The water resource system will be increasingly stressed by climate change and population growth. Loss of heavy industry will offset some of the increased domestic demand.
- Increased storage capacity has the potential to compensate for increasingly intermittent flows, but even construction of the maximum feasible storage capacity will not on its own be sufficient to adapt to climate change and supply an increasing population unless per capita demand is reduced.
- Reduction in water demand has an important role to play in mitigating drought risk, but must be very significant and sustained to offset projected population increases and the effects of climate change. Demand savings can reduce energy consumption.
- Desalination and inter-basin transfers are energy intensive so have potential to increase carbon dioxide emissions unless energy is obtained from renewable sources.

Impacts of climate change on flood risk in London

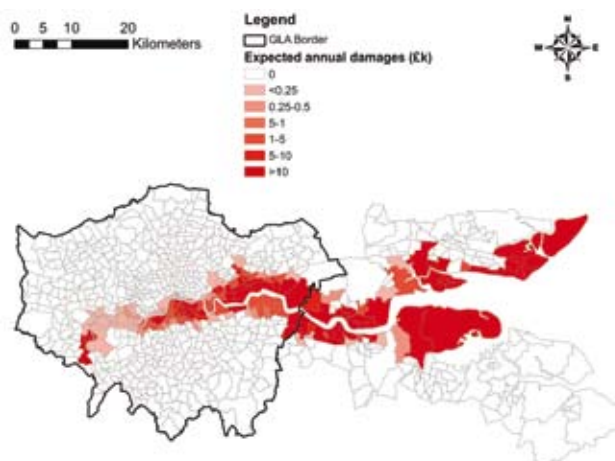
What we did:

The risk of flooding from surge tides and high flows in the river Thames was analysed using a combination of statistical analysis, hydraulic simulations and reliability analysis of flood defence infrastructure. This analysis of the probability of flooding was coupled with the results for the land use model to calculate expected annual flood damages now and in the future.

The tidal Thames floodplain includes extensive areas of development along the Thames through London and to the east. Currently there is an area of approximately 345km² at risk of flooding which contains 1.25 million people; nearly 500 schools and hospitals, 5,540ha of nationally and internationally designated sites of nature conservation importance (representing 16% of all land at risk of flooding), 2,450km of transport links (Motorway, A-Road and Rail) and 481,180 properties in the floodplain of which 476,000 are residential⁴⁰.

Analysis of flood risk is based upon analysis of surge tides in the Thames estuary and flood flows in the river Thames. Surge tide frequency will increase due to projected changes in regional mean sea level (which is projected to be in the range 0.21-0.89m by 2100). A flood risk model has been developed that includes a statistical model of storm surge and river flow, hydrodynamic simulations of water levels in the Thames and the reliability of the flood defence system and simulation of floodplain inundation. The location of new development is simulated with the land use model. In this flood risk analysis only tidal flooding, storm surges and flows in the river Thames are considered. Surface water flooding and the tributaries of the tidal Thames are not included.

Impacts of climate change will often be felt in terms of changing frequency of damaging events. Flooding impacts are therefore typically measured in terms of changing average annual losses, which involves integrating over the extreme value distribution of the climate variable of interest. These distributions are combined with damage functions, for example relating flood depth and duration, to economic damage.



Map of flood risk (in terms of expected annual damages) in 2005.

Spatial planning has an important role to play in mediating flood risk. In 2005, the expected annual damages in Greater London and the Thames Estuary is calculated as £29m, by 2100 for each landuse paradigms the increase in flood risk is:

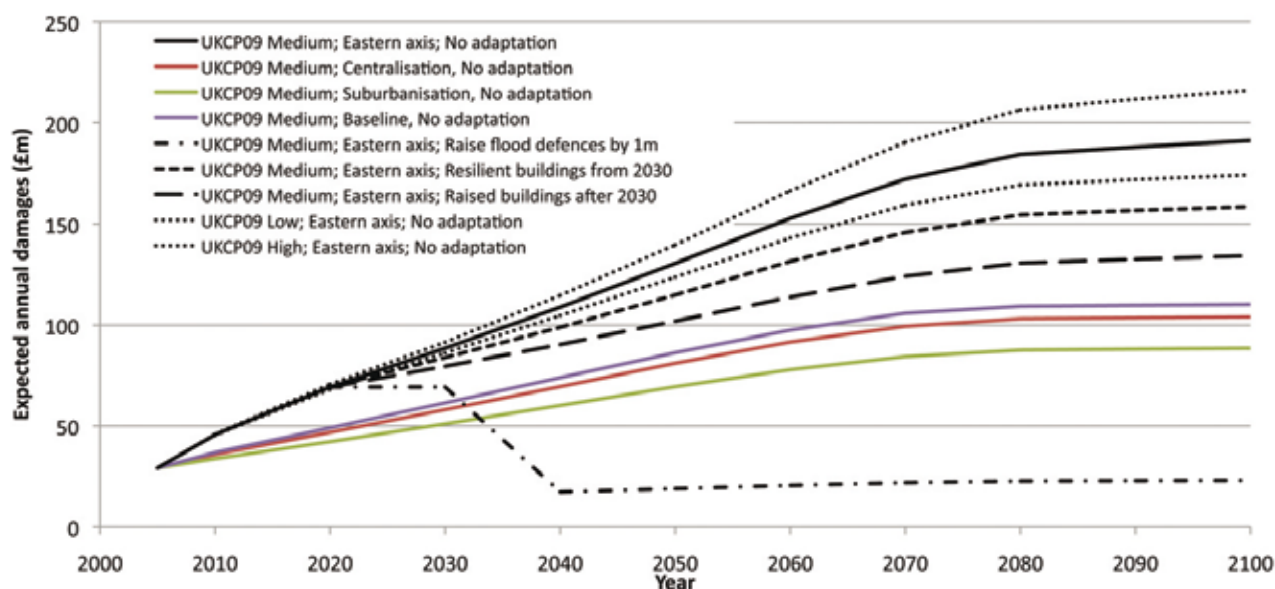
Baseline: £47m

Eastern axis: £89m

Centralisation: £43m

Suburbanisation: £33m

⁴⁰ GLA (2007). Draft Regional Flood Risk Appraisal, June 2007



Profile of flood risk (expressed in terms of expected annual damages in London and the Thames estuary, real terms and not discounted) through time on same axis for (i) the four different landuse paradigms under the UKCP09 climate change scenario, (ii) under the Eastern axis landuse paradigm for the low and high UKCP09 climate change scenarios, (iii) a range of adaptation options for the Eastern axis land use paradigm including (a) raising the existing flood defence system by 1m, (b) making all new development after 2030 fully flood resilient, (c) raising all new development (e.g. on stilts) after 2030.

The change in risk through time for each landuse paradigm is shown below. The benefits of a number of different adaptation measures against the Eastern axis development have been tested, including:

- Raising the existing flood defence system by 1m,
- Ensuring all new development after 2030 is fully flood resilient (e.g. electrics and appliances are raised, construction materials are more capable of withstanding floodwater),
- Elevating all new properties after build 2030 (e.g. placing them on stilts and perhaps using the ground floor as a car park)

Raising flood defences evidently delivers significant reductions in flood risk even under rising sea levels. However, flood defence construction is costly and only reduces the probability of flooding, rather than the vulnerability of people and amount of damages if a flood does occur. Other measures such as flood resilient construction and spatial planning to ensure no development in the most vulnerable locations of the floodplain provide significant benefits without incurring the same substantial capital costs.

What we found:

- Socio-economic change, in the form of new development, can contribute as much towards overall changes in flood risk over the 21st century as climate change.
- The land use policy most likely to increase flood risk is when development is focused along the Thames estuary (Eastern axis land use paradigm), which could triple flood risk. Stimulating development in Outer London (Suburbanisation land use paradigm) leads to the lowest increase in risk in the tidal Thames.
- Traditional adaptation to flood risk such as flood defence raising will continue to enable significant reductions in flood risk. However, to reduce vulnerability and damages, other measures such as flood resilient construction and spatial planning provide significant benefits without incurring the same capital costs.
- To meet development pressures, undeveloped land in the floodplain may need to be exploited. However, resilient development and spatial planning measures can be used to manage the flood risk associated with floodplain development.

Using integrated assessment to inform decision making

The research described in the preceding pages of this report has provided insights into many different aspects of the relationship between climate change (mitigation and adaptation) and cities. However, its main contribution has been to deal with these processes from an integrated systems perspective in order to provide internally consistent quantified scenarios of long term change in urban areas that can be used to inform decision making. By modelling urban areas as systems we can begin to understand the synergies and conflicts between different policies and can begin to develop portfolios of measures that together have a realistic prospect of achieving sustainable outcomes.

Climate change has been a remarkable stimulus to think on these extended timescales. Urban decision makers have always been conscious that urban and infrastructure development decisions can have a very long legacy, which may in practice be irreversible. Climate change, alongside a broader interest in urban sustainability, has stimulated the development of models, like the Urban Integrated Assessment Facility (UIAF) described here, that can explicitly simulate changes over extended timescales, in order to improve decision making. The timescale that we have analysed coincides with the timescale on which, with climate change in mind, infrastructure and planning decisions are now being considered. For example, the Thames Estuary 2100 project has recently appraised flood risk management decisions for the Thames Estuary on a time scale that stretches well into the 22nd Century. This new appetite on the part of decision makers for quantified evidence-based methods for appraising long term change is now met by the UIAF.

The UIAF provides diverse evidence. The number of urban processes and interactions that are incorporated in the analysis could be overwhelming. In practice therefore we

recommend the following steps (below) in the application of the UIAF.

Whilst presented in linear terms, in practice these stages in analysis are implemented iteratively via interaction between the decision makers and analysts.

We still have much to learn about how the sorts of evidence and insight that are provided by the UIAF will be used by decision makers. Whilst we have developed a number of software-based tools for practitioners to interact with, software is not the focal point of the UIAF. Rather, its development has been a process of collective learning about the most challenging questions facing cities and the ways in which quantified analysis can be used to address those questions. Through ongoing interactions with stakeholders we have refined the scenario space and have narrowed down the set of policy options in order to yield the results presented here and many other results we do not here have space to report.

Transferring the UIAF to other cities

We expect that this process of co-development will be modified and adapted to differing situations. We have been asked repeatedly about the transferability of the research to other cities. Most of the data sources listed at the end of this publication will be recognisable to those in UK local authorities as being datasets that they already make use of or can readily access. Whilst we have already emphasised that the Tyndall Centre Cities Programme has not been a software project, the software tools that we have developed (for example for transport network analysis) are readily transferable. Thus from a technical point of view, the UIAF is applicable to any UK city. The process of framing climate-related questions and understanding the relevant systems and interactions is an essential precursor to quantified analysis, which

1	Define the questions that the assessment is seeking to address.	In this analysis our focus has been upon adaptation to climate change and mitigation.
2	Identify the drivers of long term change within the urban area.	Here we have dealt primarily with socio-economic and climate drivers.
3	Identify the processes of interaction that determine long term urban change and that therefore need to be incorporated in the assessment.	The main processes of interaction we have addressed have been via the economy, land use and transport.
4	Define the policy options that are intended to be analysed and the metrics of assessment.	We have analysed policy options for: <ul style="list-style-type: none">• land use planning,• energy policy,• transport infrastructure and fuel efficiency,• water resource management,• flood risk management .
5	Develop a representative set of scenarios that spans the range of possible futures	Our scenario space incorporates <ul style="list-style-type: none">• climate scenarios (UKCP09 probability distributions)• demographic scenarios (based on ONS)• economic scenarios (low, medium and high economic growth)
6	Quantify the performance of policy options in the context of a range of different scenarios according to the defined metrics.	The results of this quantified policy analysis are described in the preceding pages.

will have to be reworked for, and matched to the needs of, any given locality. More fundamental is the need to have decision making processes in place that can assimilate the type of quantified evidence that the UIAF provides. This can challenge qualitative approaches to city planning decisions, but, on the other hand, it can also provide a new platform for collective learning and building consensus.

There will be increasing call for quantified tools in order to steer cities towards more sustainable futures. Local authorities already have to report on the progress with regard to adaptation (in National Indicator 188) and mitigation (in National Indicators 185 and 186). The government is building up its Adapting to Climate Change programme⁴¹, which is run by Defra but extends across government functions. Meanwhile, the DECC's Low Carbon Transition Plan⁴² plots how the UK will meet the 34 percent cut in emissions on 1990 levels by 2020. Implementing these strategies will require new evidence to test options and understand the synergies and conflicts, which is the aim of the UIAF.

Looking beyond the UK there is an urgent need to manage processes of change in rapidly developing cities worldwide. In many respects, rapidly developing cities are in the 'front line' with respect to climate change, in particular when, as in the case with most of the world's largest cities, they are located on coasts or deltas subject to sea level rise and subsidence. Transferring the UIAF to data-poor situations in the developing world would not be straightforward, but we have begun to think through this process working with colleagues in the municipality of Durban in South Africa, which is one of the most progressive cities with respect to urban sustainability in Africa. The UK-China Foresight flooding programme in which we have helped to develop a broad scale model of climate change, flood risk and vulnerability, is applying system-scale qualified analysis in the Taibu Basin where Shanghai is located. Whilst the datasets upon which our London UIAF relies are not available in the same format outside the UK, much of what we have learnt is transferrable. Through inter-comparison of our approaches with those of leading institutions worldwide we have developed good understanding of commonalities and differences in datasets and methodology.

Stakeholder interactions during the research programme

At the outset of the programme a number of climate related policy questions and priorities were identified based on a literature review and meeting with a number of stakeholders. During the course of the research we have sought to work closely with key London stakeholders in order to maximise the impact of the research. Our stakeholder advisory group involved representatives from the Greater London Authority, Transport for London, the Environment Agency and Thames Water, alongside two academic mentors from outside the research team. We met formally with this advisory group every six months to report on progress and obtain their advice on the direction of the research. In the intervening period we circulated

a newsletter reporting in interim results. Meanwhile, individual team members worked more closely to define research questions and identify datasets held by our London partners.



As the research has progressed we have interacted more closely on specific research questions. Interaction with the Environment Agency intensified in the build-up to publication for consultation of the Thames Estuary 2100 strategy. More recently, Richard Dawson from Newcastle University has been funded by a NERC Public Policy Placement scheme to work jointly with the GLA in testing scenarios for the new London Plan. The UIAF has helped to develop new understanding of interactions between urban functions and policy objectives. The UIAF now provides considerable flexibility in its capacity to frame and test policy options. Specifically, we have examined the range of transport futures mentioned above and continue to test a range of land use planning policies that may be considered as part of the London Plan.

Our interactions have extended beyond London to the METREX Network of European Metropolitan Regions and Areas, the UK's Core Cities, the Town and Country Planning Association and the Royal Town Planning Institute. In 2008 Dr. Sebastian Carney was awarded the Scottish Awards for Quality in Planning by the Scottish Government and the Royal Town Planning Institute for his work on development of the GRIP (Greenhouse gas Regional Inventory Project), which forms part of the UIAF. European collaboration continues via COST action TU0902, which will bring together a consortium of leading European universities and institutes, led by the Tyndall Centre, to collaborate on the topic of "Integrated assessment technologies for to support the sustainable development of urban areas.

Uncertainties in climate and socio-economic change

Long term projections of climate and socio-economic changes are fraught with uncertainty. We have made use of the UKCP09 climate scenarios which quantify aspects of climate model uncertainties for given emissions scenarios. Specifically, we have used the UKCP09 Weather Generator⁴³ to sample from the probability

⁴¹ <http://www.defra.gov.uk/environment/climate/programme/index.htm>

⁴² HM Government (2009). The UK Low Carbon Transition Plan: National strategy for climate and energy, London, The Stationery Office, London.

⁴³ Jones, P. D., Kilsby, C. G., Harpham, C., Glenis, V., Burton, A. (2009). UK Climate Projections science report: Projections of future daily climate for the UK from the Weather Generator. University of Newcastle, UK.

distributions of future climate provided in UKCP09. In other aspects of the analysis, uncertainties are dealt with through the use of a range of different scenarios. However, as with other scenario studies, these are plausible and internally consistent projections, conditional upon a clearly specified set of assumptions – they are not forecasts. We have sought to be internally consistent in the assumptions that we have made about technology and socio-economic change. However, to suppose that many of the processes we are interested in could be forecast on a timescale of decades is quite unrealistic. On the other hand, in many instances we have been able to generate reasonably plausible bounds on quantities of interest and test adaptation and mitigation policies in the context of these plausible bounds. Thus, for example, whilst we cannot specify the precise nature of future development in the Thames Gateway, we do know the nature of existing development and the extent to which vulnerability to flooding could reasonably change in future, under different land use policies. We have calculated changing flood risk taking account of these changing land use scenarios and the latest knowledge of potential for future sea level rise and changing storm surge frequency. More analysis is needed in order to understand uncertainties and their implications more fully. We are excited about the potential for new data sources, from remote sensing and pervasive sensors, to provide hitherto unavailable data streams with which to constrain the residual uncertainties in our analysis.

Limitations of existing UIAF and some further research challenges

Inevitably, the analysis has made a number of simplifying assumptions about the processes and interactions that and represented. In particular, we have not represented the potential impacts of climate change upon the urban economy and land use. One or more extremely damaging events may lead to major shocks that propagate through the economy and have lasting effects on urban land use, as Hurricane Katrina did in New Orleans. This interaction between climate, the urban economy and land use is the subject of new research in the ARCADIA (Adaptation and Resilience in Cities: Analysis and Decision making using Integrated Assessment) project, which is now under way thanks to funding from EPSRC in the Adaptation and Resilience to a Changing Climate programme.

The analysis described here has adopted a variety of aggregate approaches for estimating carbon dioxide emissions. A more complete and satisfactory approach would examine explicitly energy demands, supply, networks and flows in the urban area and their associated emissions, not only from transport and energy utilities but also in relation to water, waste and materials. Intra-urban

resource modelling, and its relation to urban dynamics and engineering infrastructure, is the subject of new research, as part of Richard Dawson's EPSRC funded research fellowship.

The climate impacts assessment in the current UIAF deals with tidal/fluvial flooding, droughts and heat waves. These are three of the major issues being addressed in the London Climate Change Adaptation Strategy⁴⁴, but the UIAF does not currently address health, the economy or the environment. Whilst ongoing work in the EPSRC funded SCORCHIO project is already refining the heat wave model, other impact modules that might be incorporated in future analysis include air quality, surface water flooding, wind, ecology and health.

The UIAF has demonstrated the capability to test adaptation and mitigation policies. However, a crucial next stage is to develop integrated portfolios of options, along with strategies for their implementation through time in the transition to a decarbonised and well adapted city. More rigorous examination of uncertainties should then form basis for development of robust portfolios of policy options. To support wider uptake, delivery and visualisation of geodata, results and uncertainties provides a mechanism to engage decision makers and civil society more broadly, through web based data provision.

The UIAF has primarily concentrated on quantified analysis with no examination of the qualitative aspects of cities, in particular concerning a city's governance. Now that a quantified assessment capacity has been established, it is important to begin to consider how the evidence it provides can be related to the governance of mitigation and adaptation in cities.

Isolating cities from their hinterland is highly problematic. The footprint of cities in terms of their demand for resources (food, water, energy) extends well beyond the city boundary, as does the problem of disposal of waste and the influence they have on transport patterns. In some respects a city-region is a more natural unit of assessment than a city on its own, and in particular might be more appropriate when addressing other UK cities

A multitude of organizations collect vast amounts of data at varying frequencies and resolutions for a diverse set of economic, social, physical and environmental attributes of urban systems. Data quality is improving as remote sensing and other monitoring techniques are becoming more accurate and densely deployed. Ecological research in the USA has benefited from structured, place-based research programmes. A similar programme focusing on climate and socio-economic change in the urban context could provide an unparalleled data repository and resource for urban research and provide important evidence and understanding of urban dynamics.

44 GLA (2008). The London climate change adaptation strategy, Draft report, Greater London Authority.

Data Sources (All web links valid on 3rd October 2009).

Data Set	Source
Climate change projections	UK Climate Projections (UKCP09). http://ukcp09.defra.gov.uk/
London's greenhouse gas emissions	Greater London Authority, London Energy and Greenhouse Gas Emissions Inventory (LEGGI). http://www.london.gov.uk/mayor/publications/2008/12/leggi.jsp
Zones of development, opportunity areas, urban green space, previously developed land within the GLA and Thames Gateway	The London Plan. Greater London Authority. http://www.london.gov.uk/thelondonplan/
Current and historic population demographics	The Office for National Statistics. http://www.statistics.gov.uk/
Sub-national population projections for England to 2031	The Office for National Statistics. http://www.statistics.gov.uk/statbase/product.asp?vlnk=997
Future population demographics, exchange rates, interest rates, GDP growth, energy demand, national taxation, government expenditure	Special Report on Emissions Scenarios (SRES). http://www.ipcc.ch/
Wards: Census Area Statistics	UK Borders. http://edina.ac.uk/ukborders/
Census data	UK Census service. http://www.census.ac.uk/
Ward level employment	The Office for National Statistics: Official Labour Market Statistics (Annual Business Inquiry) https://www.nomisweb.co.uk/
Rail network	OS Strategi Data. http://edina.ac.uk/digimap/description/products/strategi.shtml
Road network	OS Mastermap ITN Data. http://www.ordnancesurvey.co.uk/oswebsite/products/osmastermap/layers/itn/
Tube network	Transport for London. http://www.tfl.gov.uk/
Bus network	Jacobs Consulting. http://www.jacobs-consultancy.com/
Current land use and building location	MasterMap. http://www.ordnancesurvey.co.uk/oswebsite/products/osmastermap/
Index of Deprivation	Communities and Local Government. http://www.communities.gov.uk/communities/neighbourhoodrenewal/deprivation/deprivation07/
Journey to work and shop	WICID. http://cider.census.ac.uk/
Future estimates of journey to work and shop	Transport Futures Institute. http://www.transport-futures.com/
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The London Travel Report	Transport for London. http://www.tfl.gov.uk/corporate/about-tfl/publications/1482.aspx
London freight data	Transport for London. http://www.tfl.gov.uk/microsites/freight/documents/publications/tfl-freight-data-report-2008.pdf
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Road Statistics: Traffic, Speeds and Congestion	Department for Transport. http://www.dft.gov.uk/pgr/statistics/datatablespublications/roadtraffic/speedscongestion/roadstats/
Public transport statistics Great Britain - annual bulletins	Department for Transport. http://www.dft.gov.uk/pgr/statistics/datatablespublications/public/annualbulletins/
Generalised cost parameters	Department for Transport. http://www.dft.gov.uk/webtag/
Atmospheric emissions in London	National Atmospheric Emissions Inventory. http://www.naei.org.uk
Inventory of energy use	Department of Energy and Climate Change. http://www.decc.gov.uk/
Energy statistics	Digest of United Kingdom Energy Statistics. http://www.berr.gov.uk/energy/statistics/publications/dukes/page45537.html
Greenhouse gas inventory	UK Greenhouse Gas Inventory National System. http://www.ghgi.org.uk/unfccc.html
Energy consumption statistics	Department of Energy and Climate Change. http://www.decc.gov.uk/en/content/cms/statistics/regional/
Combined heat and power usage	The London Development Agency. http://www.lda.gov.uk/
On-site renewable energy database	The London Development Agency. http://www.lda.gov.uk/
Energy use statistics	Greater London Authority, London Energy and CO ₂ Inventory. http://www.london.gov.uk/gla/publications/environment.jsp
Historical flows in the Thames catchment	Centre for Ecology and Hydrology. http://www.ceh.ac.uk/data/nrfa/river_flow_data.html
Historical rainfall and temperature data	The British Atmospheric Data Centre. http://badc.nerc.ac.uk/
Operating rules for reservoirs, bulk transfer agreements, groundwater and surface water abstractions and target river flows	The Lower Thames Operating Agreement. http://publications.environment-agency.gov.uk/pdf/GETH0606BKXS-e-e.pdf
Thames Water's Water Resource Management Plan	http://www.thameswater.co.uk/cps/rde/xbcr/corp/drwmp-01-summary-overview.pdf
Flood defences	Environment Agency's National Flood and Coastal Defence Database. http://www.environment-agency.gov.uk/static/documents/Research/protocol2_fr_apr03_1567934.doc
Topography	NextMap IFSAR. http://www.intermap.com/nextmap-digital-mapping-program
Floodplain areas	Environment Agency. http://www.environment-agency.gov.uk/flood
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