ARCADIA: Key Outcomes and Messages

Key Methodological Developments:

Urban areas are particularly vulnerable to economic and social impacts of climate change, such as floods, droughts and excessive heat, due to their high concentrations of people and assets. Moreover, the increasing temperatures due to global warming are exacerbated in cities due to the Urban Heat Island (UHI) effect. In recent years cities globally have been developing strategies for responding to the risks of climate change. However, they often lack the evidence needed to make the case for and prioritise adaptation actions. Consequently, the development of adaptation strategies for urban areas requires integrative thinking to understand and model relationships between the built environment, land-use, infrastructure systems, the urban economy and climate.

The ARCADIA project has developed a new system of models for analysing climate risks and assessing the performance of options for adapting to climate change. We have used London as a case study and worked with stakeholders to ensure that the analysis is relevant to the climate risks that they face. The models developed have been integrated within the Urban Integrated Assessment Framework (UIAF) (Figure 1). The framework enables the exploration of a range of climate and socio-economic scenarios and their implications, providing a whole-system approach to assessing adaptation strategies to enhance future urban sustainability.

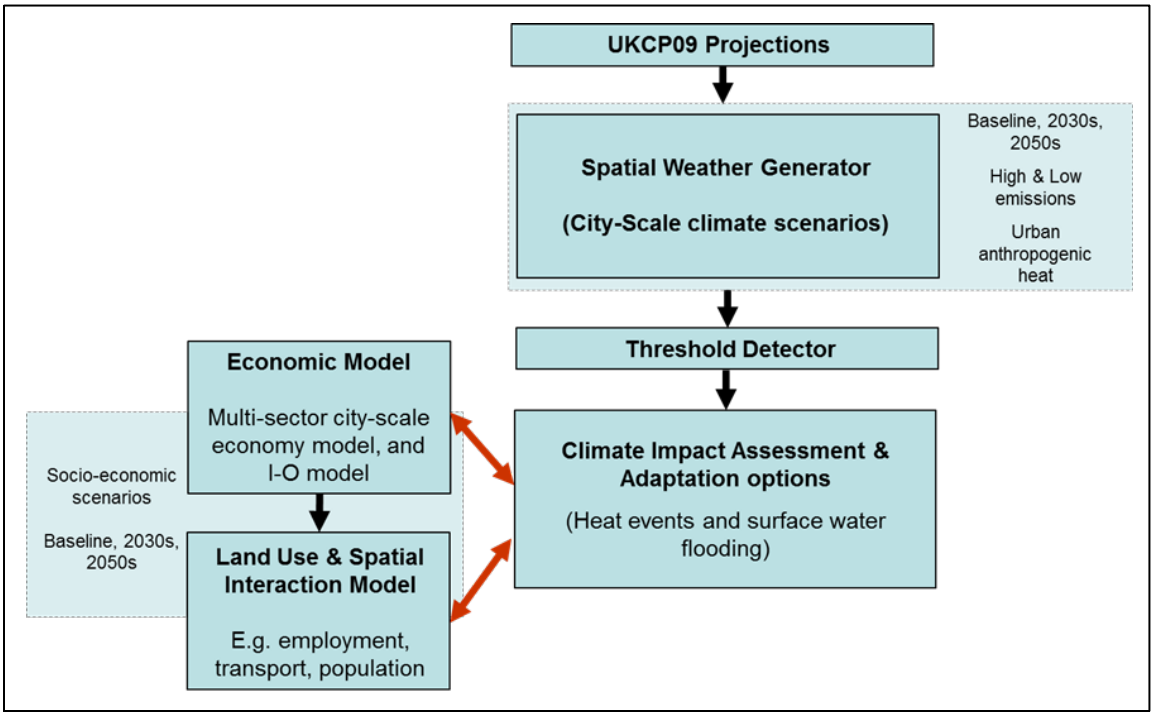

Figure 1: Overview of the Urban Integrated Assessment Framework

The analysis is novel in a number of important respects including:

- A **Spatial Weather Generator** provides time-series of fields of weather variables at a 5 km and daily and hourly resolution, and includes spatial correlation of heat and rainfall. Temperature fields take some account of the Urban Heat Island effect, and allow the potential effects of different proportions of urban land cover and emissions of waste heat on urban climate to be explored. The Weather Generator is compatible with, and a valuable addition to, the UKCP09 climate scenarios.

- A **probabilistic methodology** has been used to generate risk estimates that incorporate the effects of uncertainties in climate and vulnerability. Whilst most urban studies have focussed upon climate impacts, we are now able to generate genuine probabilistic estimates of climate risks.

- A novel input-output representation has been used to represent the effects of climate related disasters on the **economy**, and subsequent economic recovery from those disasters. The model represents the effects of disruption to supply chains and consumer demand that would result from a very severe event such as a widespread flood.

- A new model of future **land use** change, extending to the edge of the commuter belt around London, has been used to assess potential changes in vulnerability to climate change. Driven by changes in population and employment, the land use model provides an indication of the spatial distribution of future employment (by industrial sector) and population (by socio-economic class) within London, which in turn allows estimates to be made on the future land occupancy required by these competing groups.

- A complete model of the **urban transport** network has been used to estimate the potential disruptive effect of climate impacts on transport infrastructure, for example due to rail buckling in excessive heat. The transport model covers public and private transport modes. A dynamic model of demand, service quality and switching between transport modes has been implemented to simulate the effects of transport disruptions on passenger flows.

- During the research programme we have held meetings and workshop with decision-makers in London to promote uptake of the research. Further interactions with stakeholders and researchers in related EPSRC projects have been facilitated by the Adaptation and Resilience to a Changing Climate Coordination Network http://www.arcc-cn.org.uk/.

Key Results and Messages on Heat Risk:

Rail buckle events

· The total number of rail buckle events in the study area (GLA and parts of East and South-East England) are projected to increase from an average of 12 events per year (50th percentile) to 43-44 by the 2030s (low and high emission scenario respectively, 50th percentile) and to 56-70 events per year by the 2050s (low and high emission scenario respectively, 50th percentile).

· Estimated average annual economic damages in terms of repair costs increase from £119,000 (50th percentile) to £427,000-£445,000 by the 2030s (low-high emission scenario, 50th percentile) and £562,000-£696,000 by the 2050s (low-high emission scenario, 50th percentile).

· Benefits of upgraded track quality to be resilient to temperatures of 31°C (moderate track quality) and 39°C (good track quality) are significant for mitigating rail buckle events. A reduction in average annual damages of ~13% is seen in the 2050s (high emission scenario, 50th percentile), increasing to 93% for good quality track in the 2050s (high emission scenario, 50th percentile).

For policy-makers the results help highlight the potential benefits of maintenance and track upgrades to reduce track vulnerability, and highlight the range of possible temperature regimes which railways *could be operating under in the future. This will have implications for the current track standards used and development of future maintenance practices. The costs of future investments could be gauged against the economic benefits in terms of reduced frequency of buckle events.*

Speed restrictions

· The study provides damage functions showing the correlation between the magnitude of heat events in the study area and the impact of speed restrictions on the number of associated delay minutes and equivalent economic costs.

· Improved track conditions, which result in track being more resilient to higher temperatures and requiring less severe speed restrictions, are investigated to quantify benefits in terms of reduced delay minutes and equivalent economic costs.

· Damage functions showing the correlation between one or more daily buckle events and the consequences for commuters in terms of delay minutes and equivalent economic costs are provided.

· Projected costs to Network Rail and train operators of compensation and fine payments are estimated based on the estimated number of delay minutes.

Results highlight the potential economic impacts of future temperature regimes on the functioning of the railway network and the implications this may have for rail operators and commuters. Different options for maintenance and investment in infrastructure can be explored to help guide decision making. Given the projections of future change in temperature the analysis will also provide stakeholders with information to help increase resilience in the shorter and longer term, and highlights the importance of developing track maintenance regimes not only based on current weather conditions. The spatial nature of the outputs can also provide an overview of potential hot spots.

Indirect economic impacts

· Damage functions showing the correlation between direct economic costs of commuter disruption from speed restriction events and buckle events, and the indirect economic cost to the wider economy in terms of changed labour productivity.

The study provides indications of the sensitivity of GDP loss to damage in specific sectors of the economy, indicating which sectors ought to have priority in allocation of adaptation resources if economic impacts are of primary concern. For heat risk, these tend to be sectors associated with finance and professional services.

The analysis of indirect economic impacts provides more comprehensive coverage of the potential consequences of temperature change on the railway network and economic impacts to businesses and the competitiveness of the city as a whole. This information could help enhance the business case for increased investment in railway infrastructure and maintenance at a broader scale.

Mortality Risk

· Mortality risk is calculated based on epidemiological studies which correlate mortality to mean daily temperature. Future climate change is projected to have a negative impact on total heat-related mortality with 603 additional annual deaths in Greater London by the 2050s (high emission scenario median results), and 1,262 additional deaths across the whole ARCADIA study area (2050s high emission scenario median results).

· If, for example, the ratio of urban anthropogenic heat (from different urban land cover and emissions of waste heat) increases by 50% from the baseline then these figures increase to 842 and 1,643 additional heat related deaths (2050s high emission scenario median results). This highlights the additional risk which could be faced if the UHI effect continued to intensify in the future.

· While there is no generally accepted methodology and limited evidence on the effects of autonomous or planned adaptation on temperature-related mortality, one proposed method for modelling adaptation is to shift the exposure-response relationship. For example, increasing the mortality based temperature threshold by 1°C resulted in a decline in average annual heat related deaths of 41% by the 2030s (high emission scenario median results).

The results highlight the likely impact of future temperature regimes, including the additional influence of the UHI, on heat related mortality and highlight areas which are likely to be at higher risk. This probabilistic information on future temperature regimes and mortality risk will be beneficial for future adaptation planning across a range of agencies, including the health sector and built environment, and highlights the benefits which could be seen through planned adaptation to restrict temperatures in urban areas and enhance personal resilience to high temperatures.

Residential Discomfort

· A range of external temperature thresholds were defined based on published simulation studies, which account for different building stock characteristics and thermal properties, to account for the amplification of external temperatures within residential buildings. Based on the exceedence of internal temperatures of 28°C the potential number of residents at risk from heat discomfort were estimated under a range of climate scenarios.

· Results for the baseline indicate that around 45-66% of residents living in flats could be affected by thermal discomfort (median result) based on the different external temperature thresholds. In contrast 18-23% of residents living in detached homes were estimated to be at risk of thermal discomfort. This difference reflects the different characteristics and thermal properties of the building types as well as the spatial locations and concentrations of buildings within the study area.

· The percentage of residents at risk from thermal discomfort increases under all future scenarios of climate change. By the 2030s (high emission scenario, median result) 59-76% of flat based residents, and 24-29% of residents in detached properties are at risk. A 50% increase in future urban anthropogenic heat emissions would further increase the risk of thermal discomfort to residents, with 78-87% and 47-49% of residents in flats and detached properties affected respectively.

The results highlight the likely impact of future temperature regimes, including the additional influence of the UHI, on heat related residential discomfort and highlights particular areas with high concentrations of building types which are likely to be at higher risk. This probabilistic information on residential discomfort will be beneficial for highlighting the potential benefits of future adaptation options which could reduce the amplification of external to internal temperatures within the built *environment, as well as benefits which could be seen through planned adaptation to restrict temperatures in urban areas.*

Tube passenger Discomfort

· The number of days when passengers travelling on the London Underground could be subjected to discomfort due to high temperatures, and the number of passengers dissatisfied due to heat-related discomfort are estimated for a variety of climate change scenarios. Estimates are based on platform temperature sensor data from the LU; outputs from a passenger discomfort model; and the extended version of the UKCP09 spatial Weather Generator (WG).

· The results indicate the potential for widespread future dissatisfaction with the thermal environment on both platforms and in-trains. The warmer lines (Bakerloo and Central) are, as expected, the most severely affected. Median results under a 2050 high scenario indicate that all lines assessed would experience complete or near-complete dissatisfaction with the thermal environment in trains if nothing else where to change.

· Air conditioning has the potential to provide tangible improvements in thermal comfort compared to a scenario with no air conditioning, but that this measure alone would not be sufficient to maintain thermal conditions at even the present day state for many of the lines and other options would need to be considered in parallel.

The results are useful for understanding future vulnerabilities of commuters; to highlight potential benefits of adaptation options; and the scale of passengers who may be affected by climate change in the future. The analysis also highlights how future potential changes are already being considered within decision making with regards to planned adaptations to rolling stock and rail infrastructure on the London Underground.

Key Results and Messages on Surface Water Flood Risk:

In order to assess the economic and social impacts surface water flood depth maps, provided from the UK's DrainLondon project, are utilised. The flood depth maps for Greater London reflect present day climate, topographic data and information on the surface water drainage system, and illustrate at a fine resolution (5 x 5m) the spatial extent and water depth associated with rainfall events for 1/30, 1/100, and 1/200yr return periods.

By overlaying and intersecting the spatial flood maps with land-use and demographic data it is possible to identify which assets or elements would be affected by surface water flooding, and how much they are affected. The damage is estimated through depth-damage functions, which relate physical characteristics of the flood event to economic losses.

Residential and Commercial Building Flood Damage

· Damage functions provided in the Multi-Coloured Manual (MCM) for structural and content damage to residential and non-residential properties are utilised. Additional costs of damage due to outflow of contaminated water, and increased emergency costs are also assessed. For commercial buildings a sensitivity analysis is also conducted based on modelled changes in commercial floor space under future scenarios of economic development and land-use change.

· Benefits of various adaptation options are assessed including different levels of preparedness which could reflect household level protection measures (and potentially scenarios to represent additional urban greening and Sustainable Urban Drainage systems which are being investigated).

Indirect Economic Impacts

· Damage functions showing the correlation between direct economic costs of flooding to residential buildings and commercial buildings and the indirect economic cost to the wider economy.

London is considered well protected against tidal flooding but has a relatively low standard of protection against surface water flooding, with studies specifically dealing with this type of risk less common. Consequently, risk based information on the potential economic and social impacts of surface water flooding, and assessments of the effectiveness of adaptation measures, will be highly relevant if policy makers are to address such concerns in the longer-term, and strive to implement more effective and efficient adaptation measures.

In summary the ARCADIA project has developed:

1. **An analysis of the governance arrangements for adaptation**. Understanding of the rapidly evolving governance context for adaptation helped to set the scene for the ARCADIA work on urban climate impacts and adaptation
2. **A qualitative systems description of the direct and indirect impacts of climate change on urban areas, economy and society**. London's adaptation and other policies have been analysed with respect to their coverage of the direct and indirect impacts of a changing climate.
3. **A spatial weather generator for urban areas**. A new UKCP09-compliant weather generator includes spatial correlation of heat and rainfall and allows exploration of the potential effects of different proportions of urban land cover and emissions of waste heat on urban climate. The final version of this tool has been tested and a Graphical User Interface developed.
4. **Analysis of the indirect effects of climate events on the urban economy**. A small set of illustrative scenarios demonstrate how for large disruptive events the indirect economic impacts can exceed the direct impacts, although for smaller events the direct impacts dominate. The magnitude of damage is shown to depend critically on how post-event recovery resources are allocated.
5. **Analysis of the potential effects of disruption on the transport network**: a multi-model transport model has been developed which can simulate the effects of transport disruptions. This has been used to calculate the risks of heat-related disruption.
6. **Analysis of adaptation options.** The new capability for analysing urban heat and flood risks has been used to quantify the benefits of potential adaptation strategies, including thermal design of buildings and improved resilience of transport networks.
7. **Provides a methodological approach for urban integrated assessment and climate risk analysis**. The methodological approach integrates new and updated model components within an Urban Integrated Assessment Framework (UIAF) to facilitate the analysis of multiple climate risks and adaptation options for urban systems.