UNDERSTANDING CLIMATE IMPACTS ON CITIES: THE URBAN INTEGRATED ASSESSMENT FRAMEWORK (UIAF)

ARCADIA FACTSHEET 1

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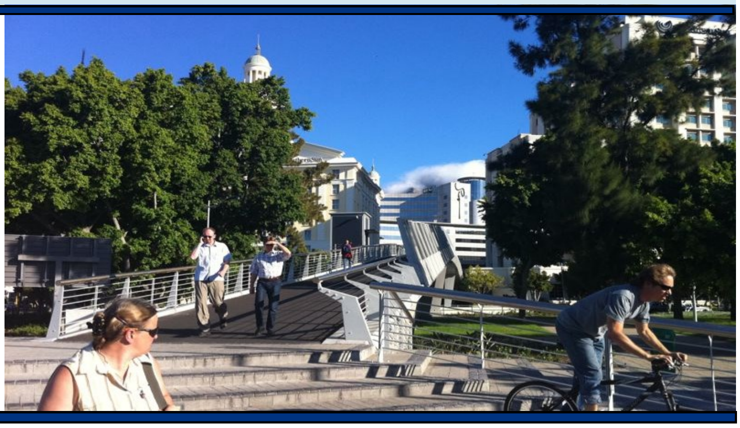
Urban areas are particularly vulnerable to economic and social impacts of climate change, such as floods and excessive heat. This is due to their high concentrations of people, assets and the Urban Heat Island (UHI) effect. This factsheet provides a description of the UIAF, which integrates a system of models to analyse climate risks and assess the performance of adaptation options to climate change in London.



Context: Benefits of using an integrated approach

- 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.
- Given the range of different actors and policies in contrasting sectors of urban areas, working at different spatial and temporal scales, developing fully integrative strategies can be complex and challenging.
- Such considerations underpinned the development of the UIAF, established to simulate processes of long-term change at the city-scale.
- The UIAF incorporates a spatial model of climate change in London, which includes the additional effects of waste heat and urban land cover on temperatures (contributing to the UHI effect); a new model of future land-use change; an economic model; and a model of the urban transport network (fig. 1).
- Integrating outputs from the models facilitates an assessment of the direct and indirect impacts of high temperatures and flooding on people, buildings and infrastructure, and an assessment of adaptation options.

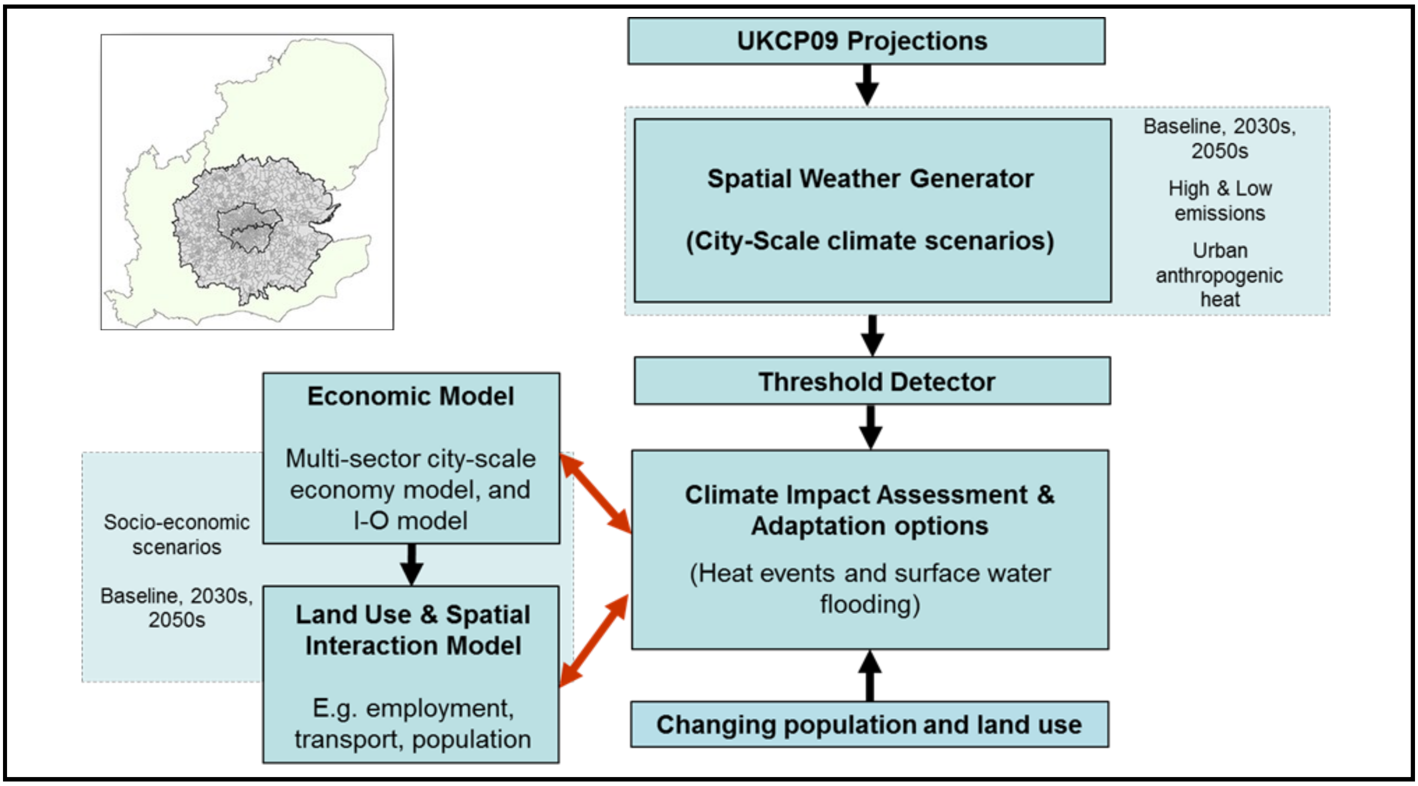


Fig. 1: An overview of the UIAF and the geographical location covered

Addressing future climate risks

- The UIAF includes a probabilistic model of climate change in London (the spatial Weather Generator), which includes the additional effects of waste heat and urban land cover on temperatures.
- The spatial Weather Generator is compatible with the UKCP09 climate scenarios. It allows a variety of emission scenarios to be tested for different time-periods to assess future weather extremes (fig. 2).
- Spatial patterns of risk can also be identified and mapped (fig. 3)

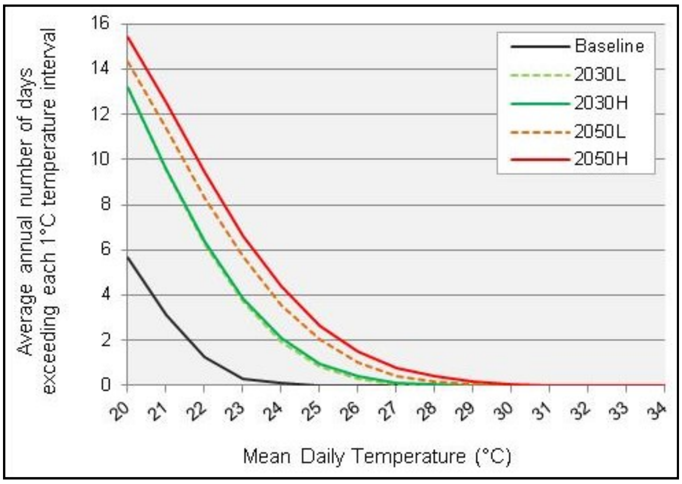


Fig. 2: The average annual number of days where daily mean temperature exceeds 20°C or more. The range in results reflects different time periods and high (H) and low (L) emission scenarios.

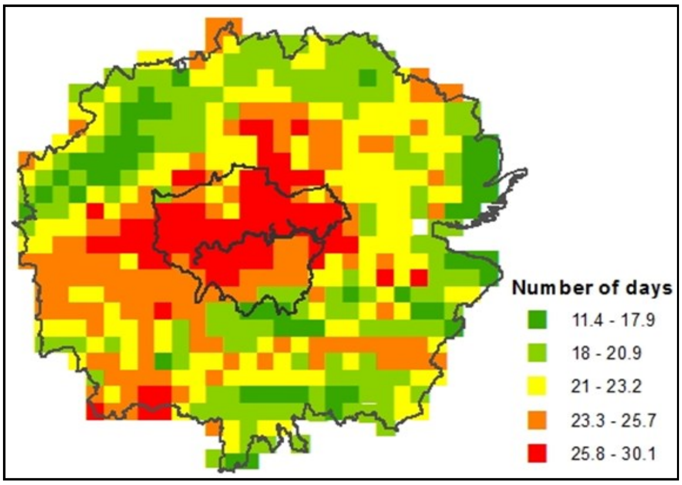


Fig. 3: A spatial map showing the annual number of days when maximum temperature exceeds 27°C in Greater London and the surrounding region (for the 2050s under a high emission scenario)

- The UIAF has been developed to address a range of climate impacts. For example, heat related mortality; impacts of heat on railway infrastructure; and damage from surface water flooding.
- The UIAF facilitates high resolution spatial modelling of impacts (e.g. fig. 4).
- Changing vulnerability due to socio-economic change as well as from climate change is also incorporated.

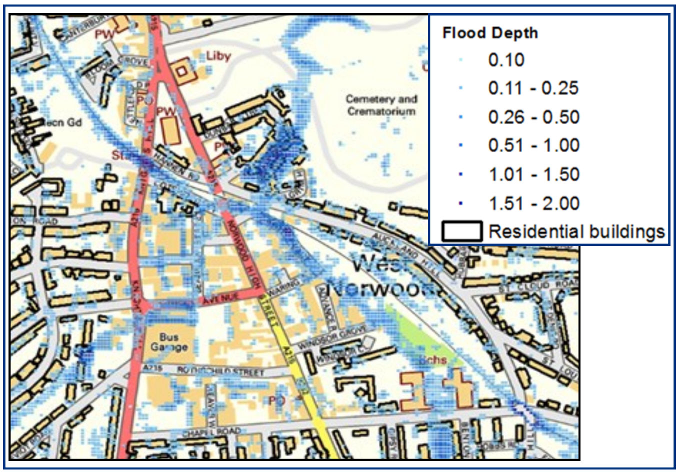


Fig. 4: High resolution modelling of flood risk

Making the case for adaptation

- The UIAF can provide information on the probabilities of extreme weather events, their characteristics, related impacts, and the implications for adaptation policies.
- Hazards are defined based on specific temperature and precipitation thresholds for each impact.
- These thresholds can be adjusted to represent and assess various impact specific adaptation options.
- The spatial information can highlight specific populations and assets at risk, and highlight hotspots which will be vulnerable to a range of impacts (e.g. fig. 5).

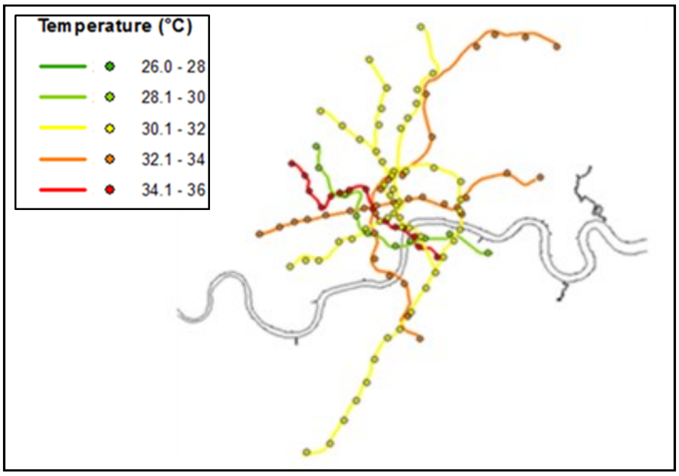


Fig. 5: Spatial pattern of maximum daily temperatures reached on trains on deep-level Tube lines . Median results for the baseline period (1960-1991)

For additional information see:

- ARCADIA factsheet number 2
- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/

PROVIDING PROJECTIONS OF URBAN CLIMATE CHANGE: A NEW SPATIAL WEATHER GENERATOR FOR URBAN AREAS

ARCADIA FACTSHEET 2

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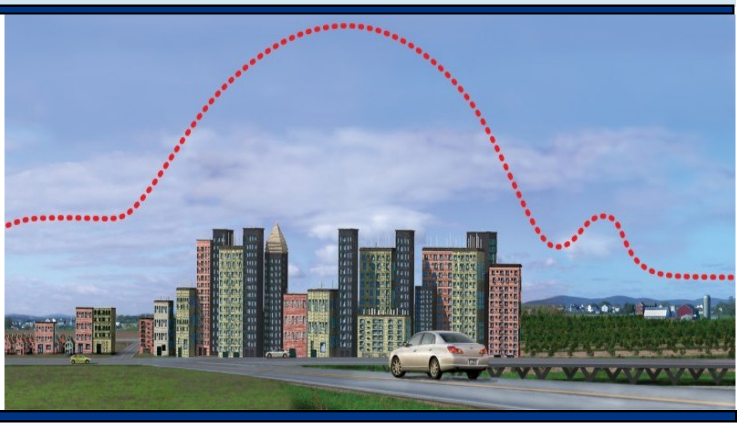
The spatial and temporal scale of climate model outputs is often inconsistent with that required for climate change impact studies. More spatially explicit climate projections can be produced by incorporating downscaling techniques that account for local climatological features. This factsheet describes a new spatial weather generator developed for urban areas and the benefits of using such a model for climate impact assessments.



Context: The UKCP09 Weather Generator

- The UK Climate Projections (UKCP09) provide climate information for the UK designed to help those needing to plan how they will adapt to a changing climate.
- The UKCP09 have been complemented through the application of a Weather Generator (WG) which provides daily and hourly time series of weather variables for present and future conditions at a 5km^2 grid resolution (fig. 1).
- The WG has been well validated against observed data from 1961-1990.
- The WG can be used to explore a range of emission scenarios and future time-periods.
- However, the UKCP09 WG does not simulate some extremes well, and does not provide spatial consistency in time across neighbouring grid cells.
- Therefore, as part of the ARCADIA project the WG has been updated to address these issues, and has been customised for specific application to urban areas.

Spatial Urban Weather Generator: Improved representation of extremes

- The WG has been updated to provide improved reproduction of extreme hourly rainfall, extreme temperatures and heatwave persistence.

Spatial Urban Weather Generator: Spatial consistency

- In the updated WG spatial fields of weather variables, which reflect both recurrent spatial patterns caused by topography and buildings and spatial dependence in weather driven by weather systems, have been considered.
- This is important so that information on daily weather events across London, and potential risk hotspots, can be provided.
- For example, the number of heat related deaths per daily heat event, or an assessment of mortality during specific heatwave events, can be assessed.

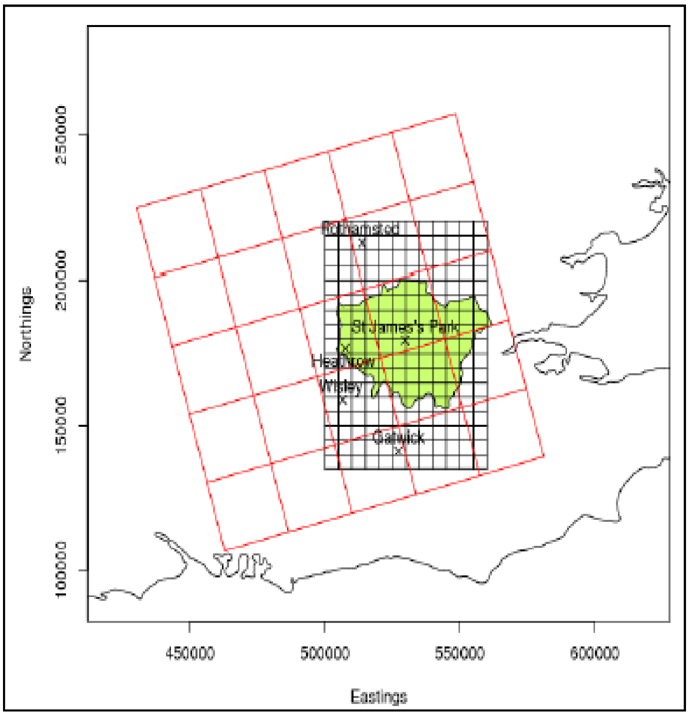


Fig. 1: Spatial WG for urban areas. Black: WG domain for London at 5km^2. Red: Regional climate model from UKCP09 at 25km^2.

Spatial Urban Weather Generator: The effect of urbanisation on London's climate

- Those living within urban areas are also particularly vulnerable to high temperatures due to the Urban Heat Island (UHI) effect, whereby temperatures are higher than in surrounding rural areas due to the heat storage of paved and built up areas, reduced radiative cooling efficiency, and waste heat from buildings, transport, and social activity.
- The effects of urban heat, due to urban land use and anthropogenic heat emissions, is incorporated in the temperature data in the updated WG (fig. 2).
- This allows the potential effects of different proportions of urban land cover and emissions of waste heat on urban climate to be explored.
- In the WG heat release accounts for ~15% of the average summer night UHI and ~42% of the average winter night UHI.
- The UHI effect results in greater changes in extreme temperatures in urban areas compared to rural areas under future projections of climate change (fig.3).
- This is beneficial as whilst past studies have highlighted the potential impacts of the UHI on climate related risks in urban areas it has not been considered explicitly in the scenarios.
- As such, these studies are likely to underestimate temperatures and impacts in urban areas.

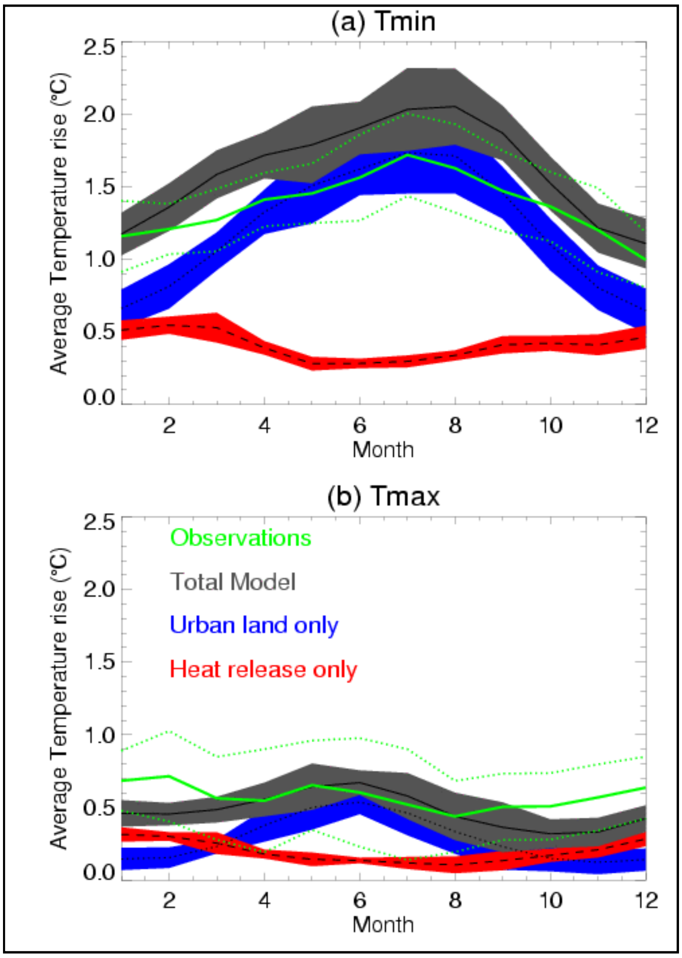


Fig. 2: The effect of urbanisation on London's climate

Benefits of using the spatial urban weather generator

- The updated WG has been extensively evaluated and validated.
- It allows the user to generate city-scale climate change scenarios consistent with the UKCP09.
- Inline with the UKCP09 the WG provides probabilistic projections which capture climate model uncertainty and natural variability.
- The WG facilitates high resolution modelling of climate and extreme weather events, such as heatwaves and extreme rainfall events, important for assessing climate related risks at a city-scale.
- The WG allows the exploration of the impacts of different future climate and urban development scenarios (e.g. reduced urban coverage and/or heat release and increasing urbanisation).
- Similarly, the effects of different adaptation policies such as urban greening, and benefits in terms of avoided climate impacts, can be explored and used to inform policy.

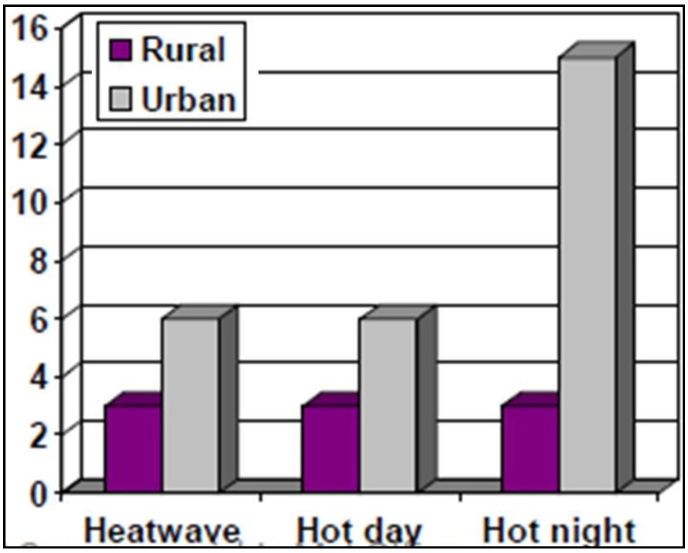


Fig. 3: Simulated increase in number of extreme days by 2050

For additional information see:

- UK Climate Projections Website: http://ukclimateprojections.defra.gov.uk/22540
- ARCADIA Website: www.arcc-cn.org.uk/project-summaries/arcadia/

UNDERSTANDING CHANGES IN SPATIAL VULNERABILITY TO CLIMATE RISKS: MODELLING FUTURE POPULATION AND EMPLOYMENT

ARCADIA FACTSHEET 3

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In order to fully understand the spatial patterns of vulnerability to future change in climate it is essential to consider changes in the urban fabric which may occur over the next century. These include spatial changes in employment, population, and patterns of urban development. This factsheet outlines a model of future population and employment patterns. The model has been developed to allow testing of spatial adaptation scenarios.

Context

- Climate change is not happening in isolation. Population growth, urban development and land-use change all have an effect on the vulnerability of urban areas to the future threats of climate change.
- It is therefore important to understand the implications of the changing spatial structure of the city under different scenarios of demographic and socio-economic change.
- The economy of a city is a key driver of patterns of growth and development, with the locations of employment and accessibility to them in turn driving the locations of population and housing.
- London is intrinsically linked to its surrounding area, with large numbers of commuters entering the city

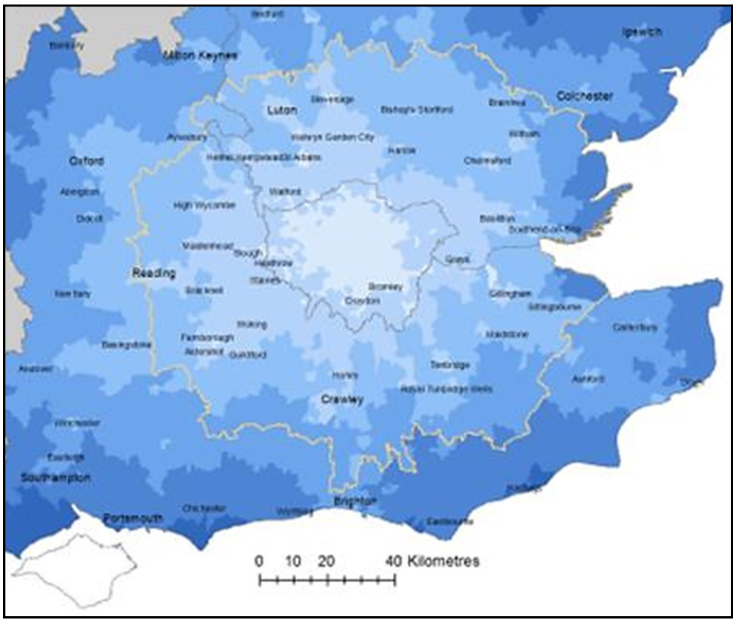

Fig. 1: Pattern of accessibility to public transport in the South East of England. Shading reflects the pattern of accessibility to public transport from high (light blue) to low (dark blue).

Understanding employment drivers

- The future location of jobs in the South East of England is a key driver of locations of population and changes to land development patterns.
- Job locations also determine the vulnerability of the city and its economy to future climate events.
- A study of drivers of current employment patterns was undertaken. This provided an understanding of how they may influence employment in the future.
- Key drivers included accessibility to airports and to the public transport system (fig. 1).
- Based on this study future employment scenarios were developed.
- The analysis focused on ten sectors representing the key employment types across London and the wider South East.
- Business Services, Financial Services, IT and Professional Services, and Construction sectors were expected to have the largest role in driving the economy of the region.
- Regression analyses were run for each sector to determine the biggest drivers of the spatial location of employment.
- The most important driver was the availability of office floor space for service-based industries, retail floor space for retail sector, and industrial floor space for manufacturing and primary sectors.

The ARCADIA Employment Location Model

- Based on the drivers of employment and employment location a model has been developed to allow simulation of possible future employment patterns under various economic and planning scenarios.
- Three planning scenarios are available: Business as Usual, Decarbonisation, and Deregulation (representing a relaxing of planning laws to encourage business growth).
- The three scenarios can be used to assess future employment locations and the effects of these changes in terms of climate hazards.
- The employment patterns are also used as a driver to the Population Location Model.

The ARCADIA Population Location Model

- The ARCADIA Population Location Model produces projections of future population across Greater London and the surrounding region.
- Future population is projected using a number of drivers and constraints.
- For example, the number of jobs in the area (estimated by the Employment Location Model) and the transport accessibility to reach these jobs are key drivers of population locations (as shown in fig. 2).
- Future patterns of population can be examined alongside future climate change scenarios to understand how vulnerability to climate hazards will change in the future.

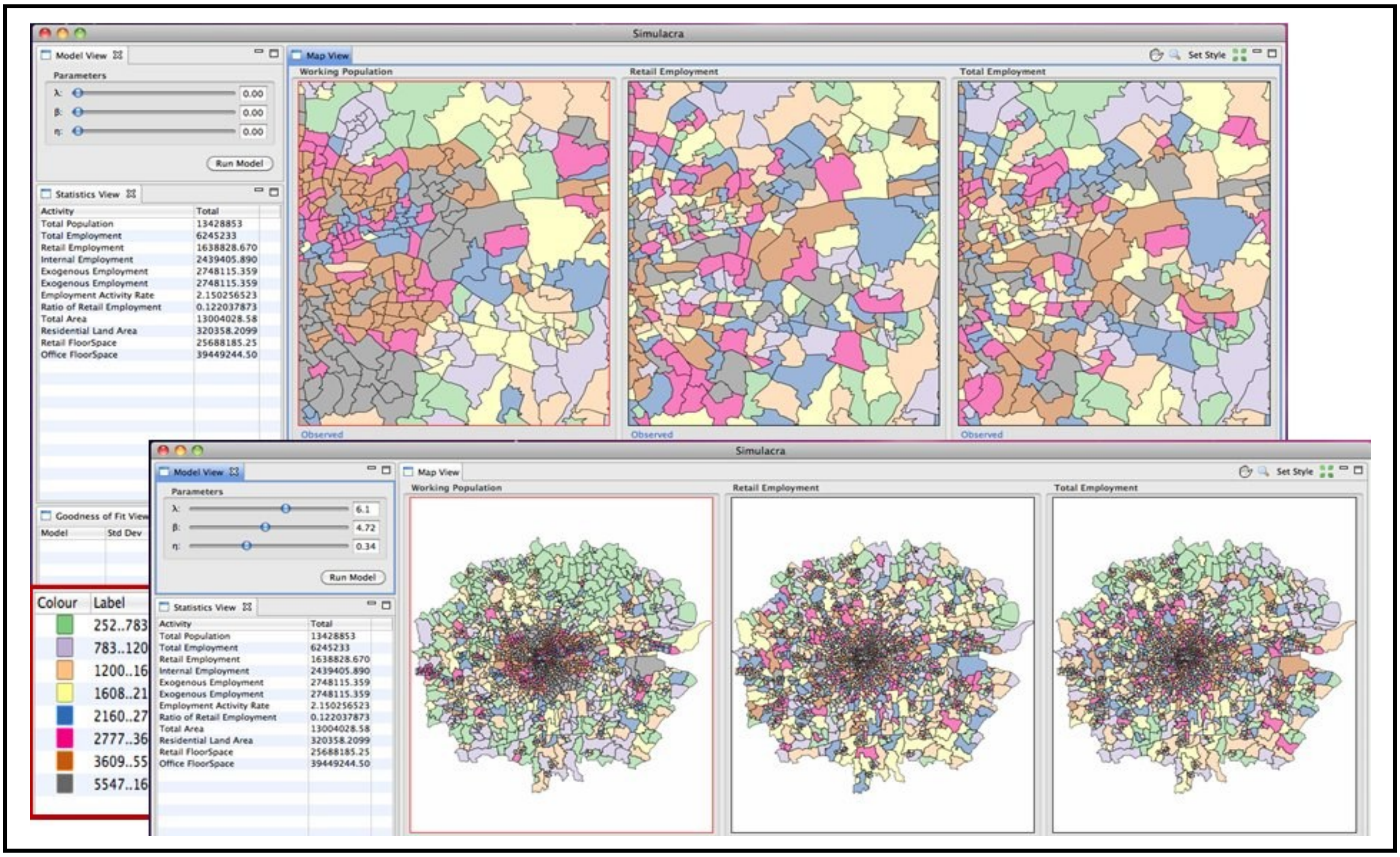

Fig. 2: An example screenshot of the ARCADIA Population Location Model, showing population (left) driven by factors such as retail jobs (centre) and total jobs (right) for the study area.

Summary

- The two models outlined above provide future scenarios of urban development, in terms of employment and population locations.
- The models produce spatial snapshots of employment and population numbers at future time periods (e.g. for the 2030s and 2050s) which allow the analysis of future vulnerability to climate change.
- Desktop and web-based versions of the models are being developed at the Centre for Advanced Spatial Analysis (CASA) to provide tools for the rapid exploration of urban patterns and future scenarios.

For additional information see:

- CASA website: http://www.bartlett.ucl.ac.uk/casa
- ARCADIA Website: www.arcc-cn.org.uk/project-summaries/arcadia/

ANALYSING THE POTENTIAL FOR CLIMATIC EXTREMES TO DISRUPT URBAN TRANSPORT SYSTEMS: TRANSPORT MODEL

ARCADIA FACTSHEET 4

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Extreme weather events can have an impact on public transport systems, directly through damage to roads or track infrastructure or indirectly due to speed restrictions imposed for safety reasons. In order to understand these impacts better, a spatial model of network disruption has been developed in ARCADIA. This factsheet examines the effects of heat on rail infrastructure and the cost of these effects in terms of disruptions to commuter journeys in London.

Context

- Extreme temperatures can cause damage to railway infrastructure through expansion of the rails and associated buckling.
- The extent of impacts will be dependent on the spatial pattern of the temperature, the maximum temperature reached, the spatial configuration of the transport network, and the condition of the railway lines themselves.
- Not only is direct damage costly to repair but it can also cause extensive disruption to commuter journeys due to imposed speed restrictions outlined by rail maintenance authorities for health and safety purposes.
- Disruption to services can also result in costly fines and compensation payments for rail operators.
- To understand the full implications of weather events on the transport network increased journey time resulting from reduced speeds on the network must be determined in conjunction with the number of passenger journeys impacted.
- Passenger delay minutes can then be quantified and monetised to provide a more comprehensive picture of economic costs.

The Transport Model

- In ARCADIA, a new transport model was developed to simulate the number of passengers using each part of the transport network for their daily journey to work.
- The transport model is GIS-based. It utilises publicly available data to construct and represent transport networks in London.
- The networks represent private car journeys on roads and trips by public transport on rail, light rail or bus.
- Observed or modelled flows of people across the city can be mapped onto the transport network based on the shortest routes between areas of residence and employment.

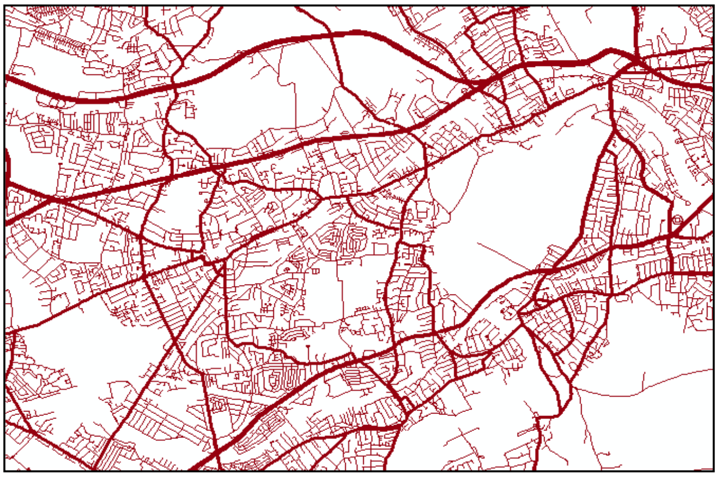


Fig. 1: A section of the road network within the ARCADIA transport model. The thickness of lines denotes the capacity of each road in vehicles per hour

- Network capacity is also included (fig.1) to capture any congestion on the networks.
- Congestion will be important when weather related disruption causes people to look for alternative routes for their journey to work.
- Any resultant congestion can further reduce journey times adding to delays in addition to those directly caused by weather events.

Linking heat events and speed restrictions

- In order to calculate the cost of commuter disruption following extreme heat events the spatial pattern of temperature and the railway infrastructure must be examined together.
- Speed restrictions are imposed when track temperatures reach a given threshold, as determined by railway maintenance authorities, and based on track conditions (table 1).
- The temperature thresholds are applied to output from the Urban Spatial Weather Generator (described in ARCADIA Factsheet 3) (fig. 2).
- A range of different time-periods and emission scenarios can be analysed to assess the probability of each threshold being exceeded on any given day, and the associated speed restrictions which would be imposed on the transport network.

Threshold	Speed restriction
<27°C	None
Poor Track ≥ 27°C < 28°C	30mph
Poor Track ≥ 28°C	20mph
Moderate Track ≥ 33°C <35°C	60mph
Moderate Track ≥ 35°C	20mph
Good Track ≥ 36°C	90mph
Good Track ≥ 42.6°C	60mph

Table 1: Thresholds of maximum external air temperature at which effects start to be felt on rail networks in the UK. For poor track condition impacts can occur at relatively low temperatures which are projected to be surpassed with higher frequency under future climate conditions.

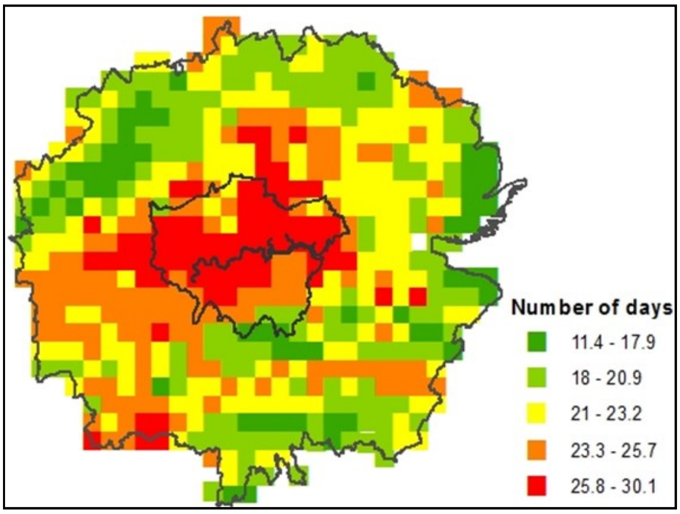


Fig. 2: A spatial map showing the annual number of days when maximum temperature exceeds 27°C in Greater London and the surrounding region (for the 2050s under a high emission scenario)

Modelling transport disruption and commuter delays

- Based on the thresholds outlined above spatial maps of daily heat events and their equivalent impact on railway speeds can be linked to the transport model.
- By overlaying this data onto the railway network the disruption to commuter journeys, and propagation of these impacts over time, can be modelled (fig. 3).
- The total impact in terms of delay minutes for each event day can be calculated for each scenario and different levels of track condition.
- Passenger delay minutes can be converted to economic costs and different scenarios compared.
- The spatial transport model allows the wider impact of heat-related speed restrictions on journey times to be examined for London and the wider region.
- Key infrastructure vulnerabilities can be identified, highlighting the transport links whose failure would cause the largest commuter disruption and costs.

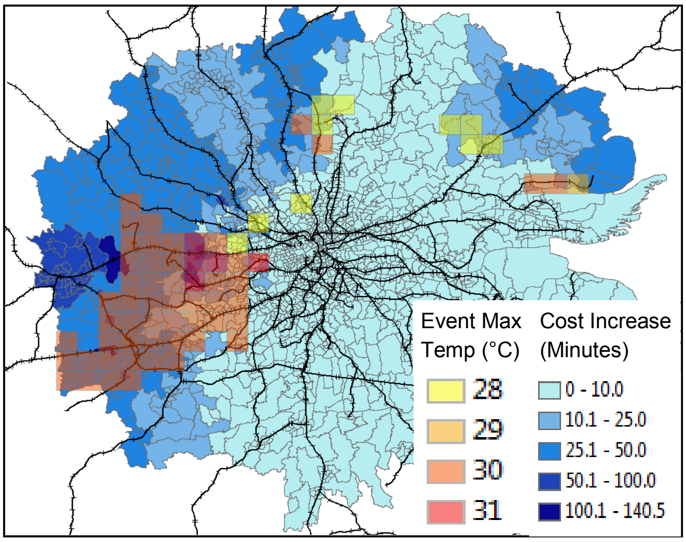
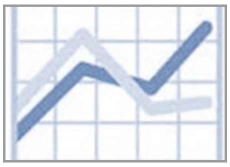


Fig. 3: An example disruption output for the public transport network for one extreme heat event day. The increased journey costs (in terms of time) resulting from heat speed restrictions can be seen.

For additional information see:

- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/
- Newcastle University CESER Website: www.ncl.ac.uk/ceser/researchprogramme/informatics/transportanalysisforclimateimpactassessment/

CLIMATE CHANGE AND ECONOMIC VULNERABILITY: AN ECONOMIC MODEL TO ASSESS INDIRECT ECONOMIC IMPACTS



ARCADIA FACTSHEET 5

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Extreme weather events can have both direct and indirect effects on an economy. This factsheet outlines a new Adaptive Regional Input Output (ARIO) model of London's economy which can be used to assess such indirect impacts. Results demonstrate that indirect effects can be on the scale of direct effects. Consideration of only direct economic effects in climate adaptation can lead to incorrect conclusions as to where adaptation resources should be directed.

Context

- Climate related damage to one sector of an economy (such as transport) can lead to economic losses in other sectors, even if the latter sectors are not directly damaged.
- Including these indirect economic effects on measures such as GDP can significantly increase the perceived economic costs of climate change, as well as altering selection of strategies to reduce risks through adaptation.
- Gaining a scientifically sound understanding of both the direct and indirect effects of extreme weather events on an economy, and how these can be reduced through adaptation, is crucial to climate policy.

Method

- Direct economic losses from extreme weather events can be defined as the physical damage to e.g. land, capital and machinery, usually seen immediately. Direct losses can subsequently cause business interruptions, usually seen in the short to medium-term.
- One way of quantifying direct and indirect losses is through Input-Output (IO) analysis. This captures interactions between industries which both produce goods and consumes goods from other industries in order to produce such goods.
- An input-output model of London's economy (ARCADIA ARIO) was developed based on the UK macroeconomic model of Cambridge Econometrics.
- The model reflects interactions between 42 economic sectors.
- The model is used to understand the sensitivity of London's GDP to direct losses from extreme weather events.
- The model estimates the length of time required before the economy fully recovers, which may be several years depending on the scale of original damage (fig. 1).
- The model also allows for simulation of different modes of allocating resources to the recovery effort, with options being to replace production capacity only as demand returns or to stimulate recovery by investing in replacement ahead of demand.

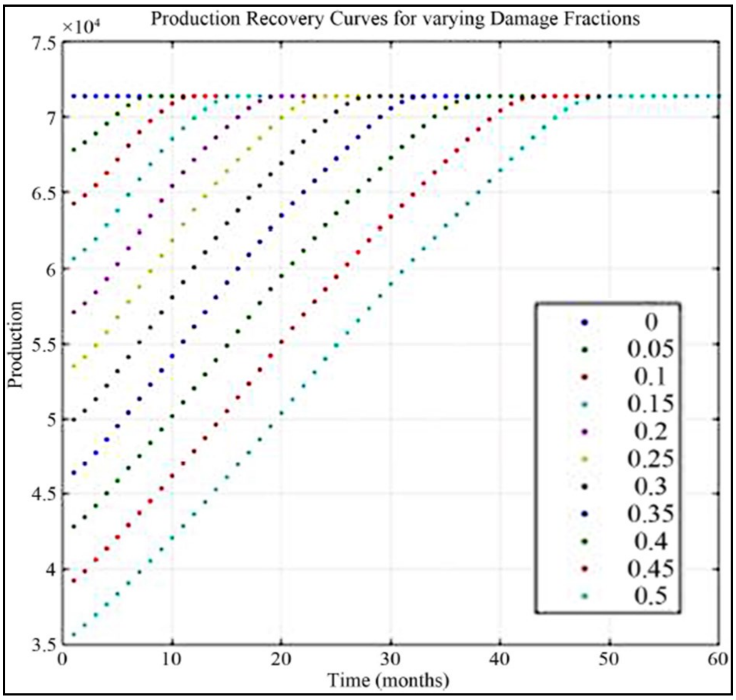

Fig. 1: Plots showing the recovery of production over time depending on the ratio of direct losses

Key economic findings

- Indirect economic effects will generally be on the order of 30 to 50% of the direct effects, rising to 100% in the most extreme cases of damage to production capacity.
- The analysis is useful up to damages of about 50% of the production capacity. Beyond that level of damage, the structure of the economy is likely to change and such models are not reliable guides to understanding economic recovery.
- The length of time for recovery can be significantly shortened by government policies that stimulate the return of production capacity ahead of the return of demand (fig. 2).
- For London, the economy is most sensitive to damage within the Professional Services and Distribution sectors, at least in regard to indirect GDP losses (fig. 3).
- This is due to both to the size of these sectors, and to their crucial roles in many other sectors of an economy such as London's.

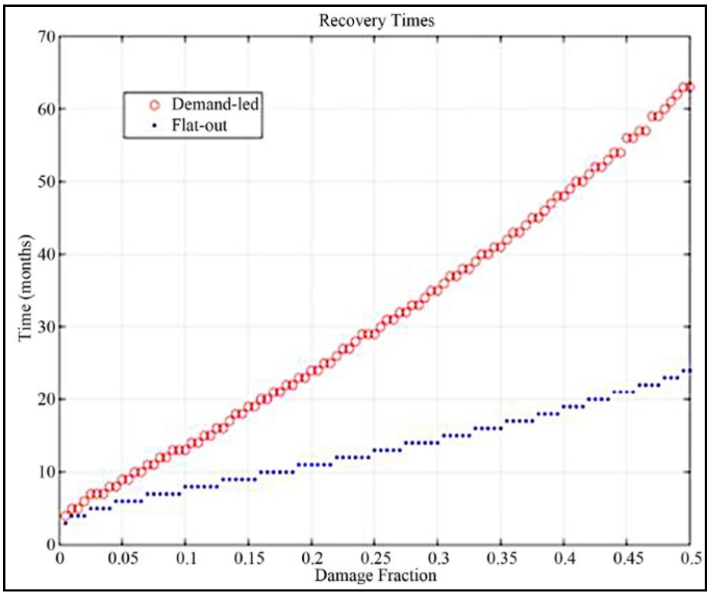

Fig. 2: Recovery time for London's economy when replacement of damaged production capacity is demand-led (red), and where resources are devoted to recovery in advance of demand (blue). The x-axis shows the fractional direct damage to production capacity due to an extreme weather event.

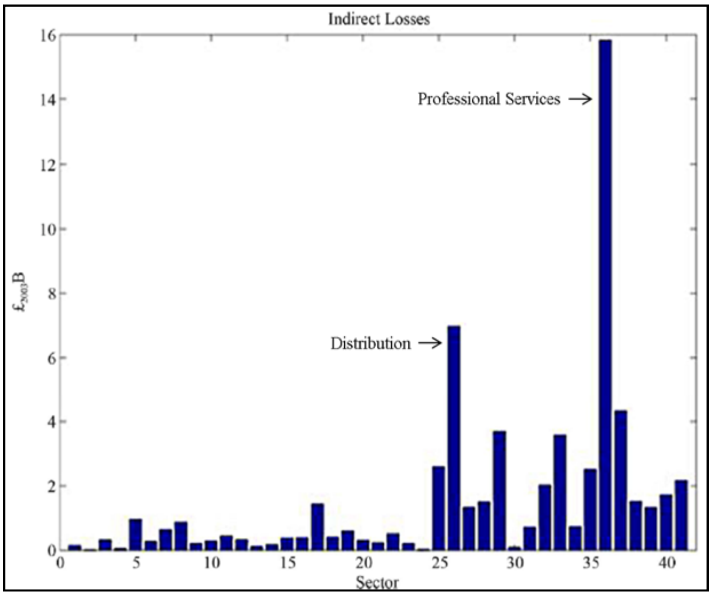

Fig. 3: The sensitivity of London's economy, in terms of indirect losses (in billion £), when the same percentage of direct losses to production capacity is applied to each of the 42 sectors of the ARCADIA ARIO model in turn, and assuming no other sectors are affected.

Linking to other components of ARCADIA

- The ARCADIA ARIO model focuses on the economic damage and recovery caused by damage to production capacity.
- This damage is represented as a percentage change in production capacity following an extreme weather event.
- The model can be combined with results on direct economic damages from extreme weather events, calculated as part of the ARCADIA project.
- The vulnerability of an economy and its economic sectors to extreme weather events can then be determined using the ARCADIA ARIO model.
- For example, the indirect effects of damage to transport infrastructure, disruption of labour and the supply of goods, and damage to physical capital such as commercial and residential buildings.

Policy relevance

- The modelling approach can provide information to better quantify the full economic impacts of an extreme weather event on a city's economy.
- It highlights the economic sectors where investments in adaptation may be most effective at reducing the vulnerability of the economy.
- It can be used to guide allocation of recovery resources following an event..

For additional information see:

- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/
- 4CMR Website: http://www.4cmr.group.cam.ac.uk/
- Crawford-Brown *et al*., " Vulnerability of London's economy to climate change: Sensitivity to production loss", Journal of Environmental Protection, 2013. http://www.scirp.org/journal/PaperInformation.aspx?PaperID=33120

MODELLING THE IMPACTS OF CLIMATE CHANGE ON CITIES: HEAT RELATED MORTALITY AND ADAPTATION OPTIONS

ARCADIA FACTSHEET 6

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High temperatures and heatwaves are associated with large impacts on society. This factsheet provides information on the effect of climate change and an intensification of the Urban Heat Island (UHI) effect on mortality risk. This risk can be reduced through adaptation strategies aimed at increasing resilience to high temperatures and reducing anthropogenic heat emissions. The greatest benefits are seen when both strategies are implemented in parallel.

Context

- High temperatures and heatwaves are associated with large impacts on society. For example, increasing mortality risk to vulnerable sections of the population.
- People are generally acclimatised to their local climates but there are limits to the amount of heat exposure an individual can tolerate. Beyond this threshold people can suffer from heat exhaustion and heat stroke which can result in death.
- Those living within cities are also particularly vulnerable to high temperatures due to the UHI effect. The UHI will be affected by future climate change as well as changes in land and energy use.

Method

- Heat related mortality can be calculated based on epidemiological studies of mortality.
- These studies highlight historic relationships between mortality statistics and daily temperature data (fig. 1).
- These relationships are applied to current and future temperature time-series data, provided by the urban spatial weather generator, to estimate future mortality risk.
- A mean daily temperature threshold of 19.2°C was used, above which heat related mortality increases on average by 3.1% per 1°C rise.
- Probabilistic results are able to be provided for a range of climate scenarios and time-periods (e.g. fig. 2 shows results for the 2030s and 2050s assuming high and low emissions).
- Adaptation is considered by shifting the threshold value by 1°C and 2°C.
- This illustrates the effect of autonomous or planned adaptation on heat related mortality. For example, by decreasing external temperatures or increasing personal resilience to heat through behavioural change or natural acclimatisation.

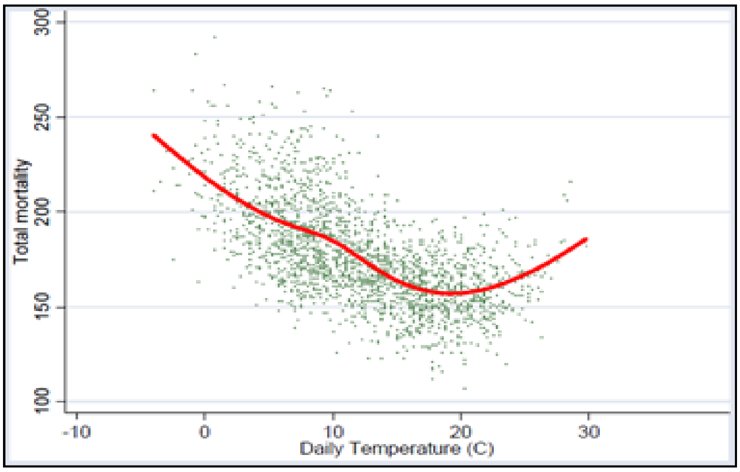

Fig. 1: Daily temperature vs. mortality in London

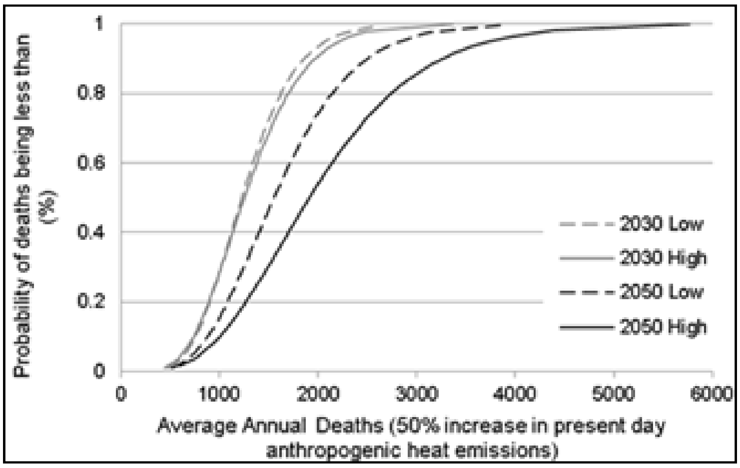

Fig. 2: Probability of average annual heat mortality

Heat related mortality risk

- If anthropogenic heat emissions increase by 50% from the present day, increasing the UHI intensity, 842 additional heat related deaths per year are projected for Greater London by the 2050s (median result, high emission scenario).
- If anthropogenic heat emissions were stabilised at the present level this would be reduced to 603 additional heat related deaths per year in Greater London by the 2050s (median result, high emission scenario).
- This highlights the potential benefit, in the form of reduced mortality, that stabilising or reducing anthropogenic heat emissions could have at a city level, for example through urban greening schemes and reduced energy use.
- Increasing the mortality temperature threshold by 1°C could reduce annual heat related mortality by 32 to 42% depending on the climate scenario used.
- Increasing the mortality temperature threshold by 2°C could reduce annual heat related mortality by 57% to 69%.
- Therefore, it is important that heat-related adaptation is considered in terms of measures to restrict temperatures in urban areas as well as by implementing adaptive measures to deal with residual temperature increase.
- The greatest benefits are seen when both strategies are implemented in parallel (fig. 3).

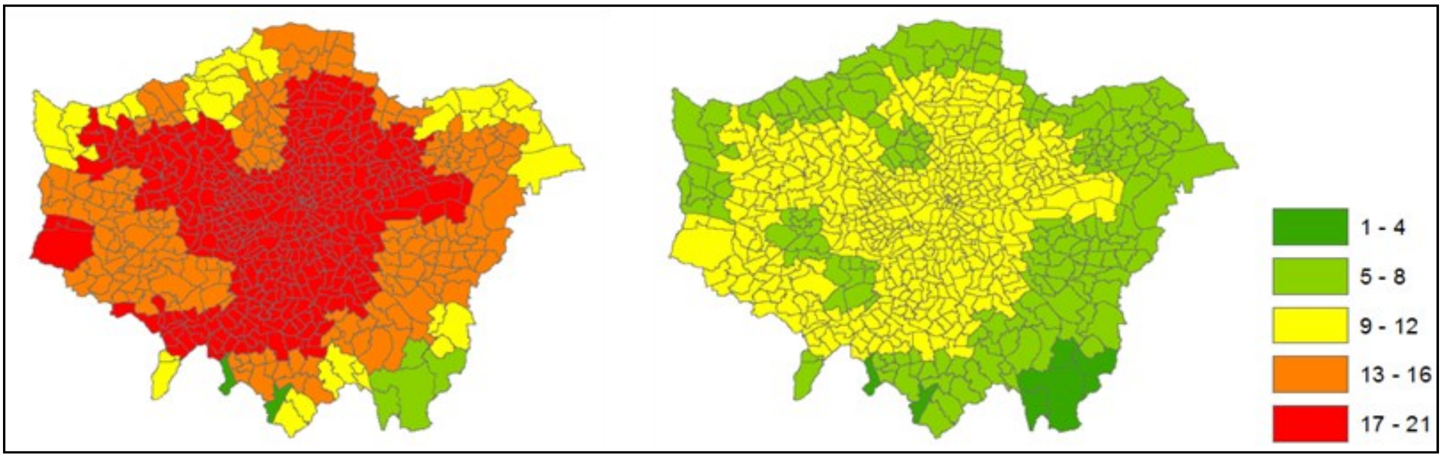

Fig. 3: A comparison of the spatial pattern of annual heat related mortality in Greater London for the 2050s (median result, high emission scenario) with no adaptation (left) and adaptation (right)

Heat related mortality of daily events

- Heat related mortality can also vary widely on any given day.
- An advantage of the spatial weather generator is that it provides coherent data across grid cells so that information on daily events can be assessed.
- Results highlights that both the frequency of days and the number of deaths per day are set to increase by the 2050s (fig. 4).
- This approach could also be used to assess mortality change during future heatwave events.

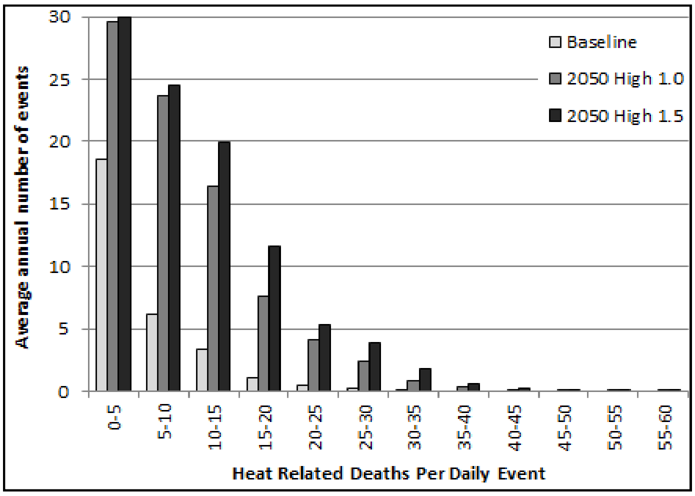

Fig. 4: Frequency of heat related deaths in Greater London assuming anthropogenic heat emissions remain stable (1.0) and increase y 50% from the baseline (1.5)

Policy relevance

- The modelling approach can provide information to help facilitate the coordination of policy makers from different areas.
- It highlights potential benefits of adaptation, which may cross policy areas.
- It can be used to inform and improve the resilience of urban areas and their inhabitants.

For additional information see:

- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/
- ARCADIA Factsheet 2

MODELLING THE IMPACTS OF CLIMATE CHANGE ON CITIES: HEAT RELATED RESIDENTIAL DISCOMFORT AND ADAPTATION OPTIONS

ARCADIA FACTSHEET 7

Contact: jim.hall@eci.ox.ac.uk katie.jenkins@ouce.ox.ac.uk

High temperatures and heatwaves are associated with large impacts on society. This factsheet highlights the effect of climate change and an intensification of the UHI on residential discomfort. This risk can be reduced by implementing adaptation strategies to increase the resilience of buildings to high temperatures, and through adaptation strategies to reduce anthropogenic heat emissions. The greatest benefits to residents are seen when both strategies are implemented in parallel.

Context

- Overheating of buildings in summer, and the associated thermal discomfort people face, is likely to become increasingly severe under future climate change.
- Residential buildings can also amplify outside temperatures, dependent on architecture, building type, construction material, ventilation, and external weather characteristics.
- Whilst there are no standard overheating limits to guide residential building design, internal temperature thresholds above which people will feel discomfort have been defined, for example 26 to 28°C for bedrooms and living space.

Method

- Studies have suggested that external temperatures can be amplified by 0.7 to 1.5°C for terraced buildings; 1.7°C for semi-detached buildings; 0.7 to 1.5°C for detached buildings, and by -0.8 to 2.7°C for flats.
- This provides an indication of overheating risk related to the basic thermal properties of different building types (assuming natural ventilation and no air conditioning).
- In this study it is assumed that people will feel discomfort in living spaces when internal temperatures reach and exceed 28°C.
- An equivalent external temperature threshold which relates to this internal temperature threshold is estimated for each building type based on the amplification data outlined (table 1).
- The temperature thresholds are applied to current and future temperature time-series data from the urban spatial weather generator.
- Spatial footprints of heat events, and how such risks could change in the future, are created.
- The event maps are linked to residential population to calculate the potential number of people at risk from thermal discomfort for each building type.

Building type	External to internal temperature amplification range	Lower limit for external maximum temperature threshold	Upper limit for external maximum temperature threshold
Terraced	0.7-1.5	26.5	27.3
Semi-detached	1.7	26.3	26.3
Detached	0.7-1.5	26.5	27.3
Flats	-0.8 – 2.7	25.3	28.8

Table 1: The temperature thresholds used to define residential discomfort for a variety of housing types

Residential thermal discomfort

- Under future scenarios of climate change the average annual number of days when thermal discomfort could occur increase compared to the baseline.
- Correspondingly, the number of residents at risk from thermal discomfort increase under all scenarios.
- For the baseline period 45 to 66% of residents living in flats could be affected by thermal discomfort (median result). This is dependent on the external temperature threshold used (fig.1).
- In contrast 18 to 23% of residents living in detached homes could be at risk.
- By the 2030s 59 to 76% of flat based residents and 24 to 29% of residents in detached homes could be at risk (high emission scenario, median result).
- If anthropogenic heat emissions also increase then 78 to 87% and 47 to 49% of residents in flats and detached properties could be at risk.
- The results reflect the underlying characteristics and thermal properties of the building types; the location, concentration, and number of residents living in each property type; and the localised temperature regimes.

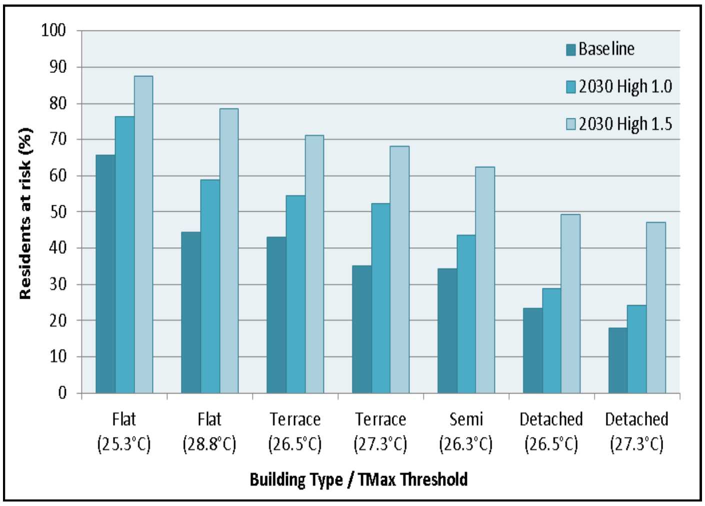

Fig.1: Residents at risk from thermal discomfort per heat event (median results). Results for the 2030s assume that urban anthropogenic heat emissions remain stable (1.0) and that they increase by 50% (1.5).

Making the case for adaptation

- Increasing the resilience of buildings, illustrated by increasing the external temperature threshold of flats from 25.3 to 28.8°C, results in 22 to 43 less event days per year by the 2050s (high emission scenario).
- This demonstrates potential benefit of adaptation strategies aimed at increasing building resilience to high temperatures, such as through improved ventilation or increased shading of buildings.
- Adaptation strategies to stabilise anthropogenic heat emissions, e.g. through urban greening schemes and reduced energy use, will also be beneficial for reducing residential thermal discomfort.
- If anthropogenic heat emissions remain at the present day level, alongside adaptation at a building level, then the number of event days could be reduced by 24 to 52 days per year by the 2050s (high emission scenario) (fig. 2).
- The greatest benefits are seen when both strategies are implemented in parallel.

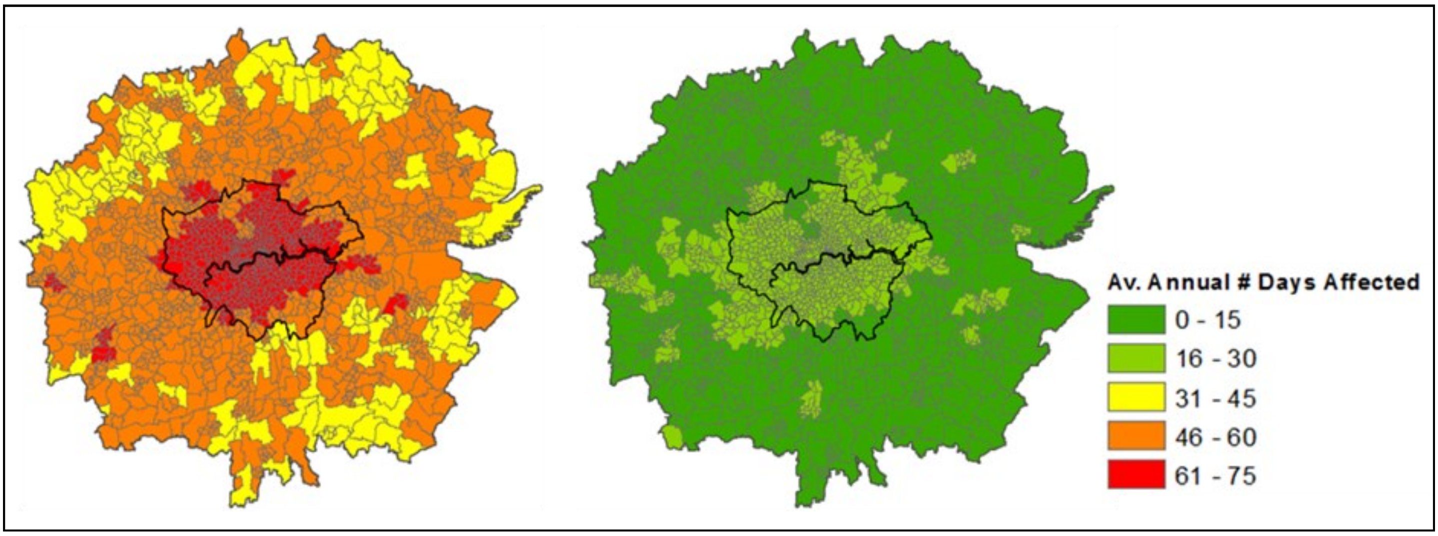

Fig. 2: Average annual number of days residents could be at risk from thermal discomfort for the 2050s (high emissions) assuming no adaptation (left) and adaptation strategies aimed at increasing building resilience and stabilising anthropogenic heat emissions (right)

For additional information see:

- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/
- ARCADIA Factsheet 2

MODELLING THE IMPACTS OF CLIMATE CHANGE ON CITIES: HEAT RELATED IMPACTS ON TUBE PASSENGER DISCOMFORT

ARCADIA FACTSHEET 8

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Underground railway systems can become very warm leading to passenger discomfort. This can become particularly problematic during periods of high temperature. Longer-term effects of climate change on passenger discomfort may also be an important consideration for railway planners. This factsheet highlights the effect of climate change on passenger discomfort in London and an initial assessment of adaptation options aimed at lowering temperatures.

Context

- Underground railway systems generate heat from the operation of trains, equipment, and passengers. This heat raises tunnel and station temperatures above background soil temperatures.
- Hot weather, ventilation assets, changing passenger demand and service expectations have all caused increased attention on thermal comfort on underground railway systems such as London's Tube.
- Of particular concern for London is deep level tube lines which tend to be the warmest, and have limited capacity for natural ventilation and limited space for saloon cooling.
- Improvements to ventilation and saloon cooling will be important to consider.
- However, a longer-term assessment of the effects of different climate change scenarios will also be important to help inform longer-term planning by railway and infrastructure operators, particularly those with limited space for saloon cooling.

Method

- The focus is on passenger discomfort on tunnelled sections of the Bakerloo, Central, Jubilee, Northern, Piccadilly, and Victoria lines (fig.1).
- These are deep level lines and do not currently have cooled trains.
- An external maximum temperature threshold of 27°C is used to define days when passengers will start to feel discomfort on the these lines.
- The temperature threshold are applied to current and future temperature time-series data, provided by the urban spatial weather generator, to provide spatial footprints of daily heat events.

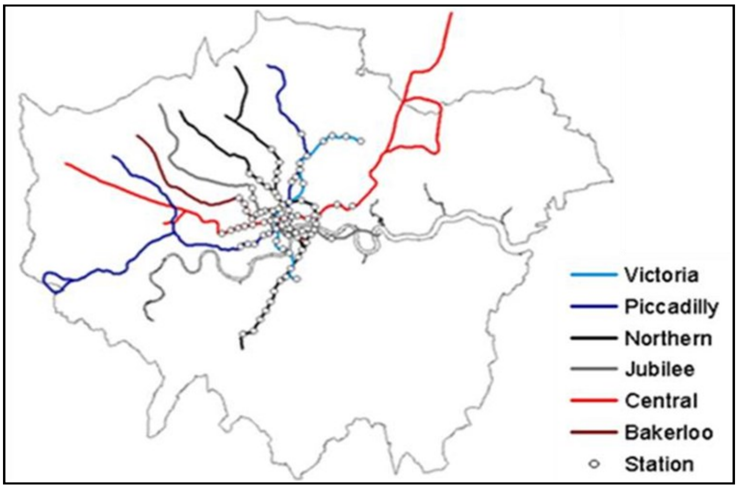

Fig. 1: Geographical position of Tube lines and underground stations covered

- For each Tube line internal temperature data from London Underground (LU) allow ticket hall, station, and train temperatures to be estimated as a function of the external temperature.
- Using this data the number of passengers who are likely to be satisfied or dissatisfied with thermal conditions on the Tube are calculated using a thermal comfort model provided by LU.
- The thermal comfort model considers factors such as outside conditions, duration in the environment and air movement to capture how thermal sensation may vary across a Tube journey.
- As an air conditioned train is expected to be 2 to 4°C cooler than a non-air conditioned train the benefits of adaptation via air conditioning is assessed by adjusting estimated train temperatures by 2 to 4°C.

Future temperatures on the LU

- Internal temperatures were predicted to increase from the baseline on all Tube lines assessed under future scenarios of climate change.
- By the 2050s (high emission scenario) temperatures on the deep level lines increase from the baseline by 1.5 to 1.8°C, 1.2 to 1.3°C, and 1.4 to 1.6°C for platforms, ticket halls and trains respectively (fig. 2).
- If anthropogenic heat emissions also increase by 50% from the present day temperatures increase by an additional 0.2 to 0.3°C.

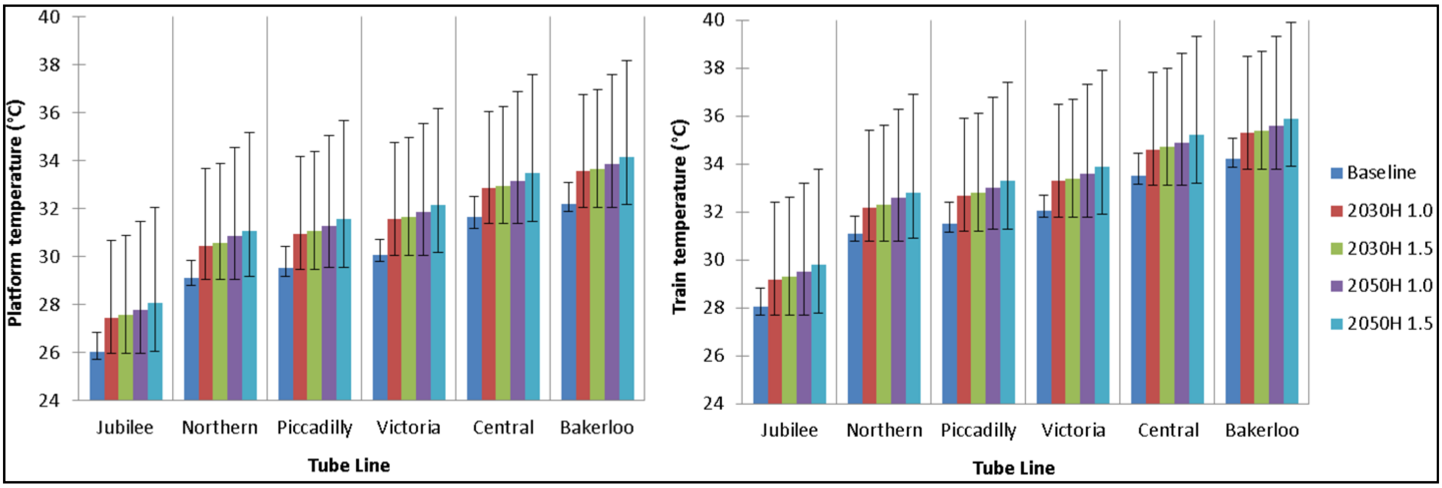

Fig. 2: The impact of various climate change scenarios on internal platform and train temperatures (median results). Black lines denote the 10th and 90th percentile

- The spatial distribution of temperatures across Tube lines can also be mapped (fig. 3).
- This is important to consider for adaptation planning and for identifying specific risk hot spots.
- Median results for the 2050s (high emission scenario, 50% increase in present day anthropogenic heat emissions) result in train temperatures of 34 to 36°C across the Bakerloo and Central lines.

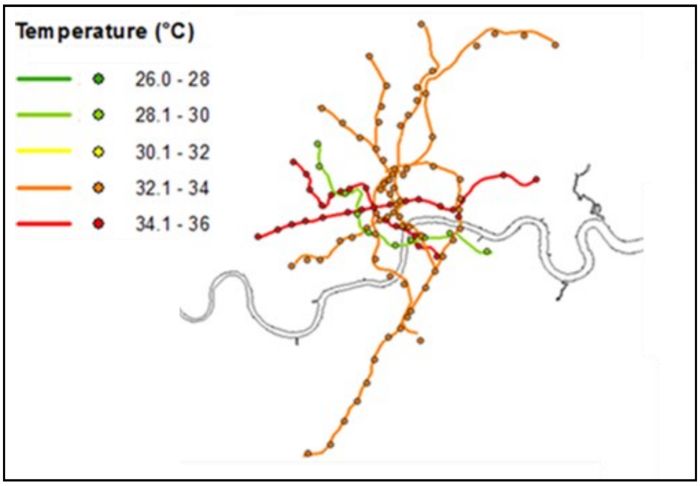

Fig. 3: Spatial pattern of maximum daily temperature on trains (2050 high emission scenario, median result)

Passenger discomfort on the LU

- The Central and Bakerloo lines appear particularly problematic in terms of passenger discomfort.
- As well as saloon cooling further infrastructure measures to reduce tunnel and platform temperatures will be required.
- On the Northern, Piccadilly, and Jubilee lines noticeable benefits could be gained from saloon cooling (fig. 4).
- LU's Deep Tube Programme is proactively investigating ways to provide further capacity as well as saloon cooling as part of upgrades.
- This method can also be informative for other railway and infrastructure operators around the world facing similar issues.

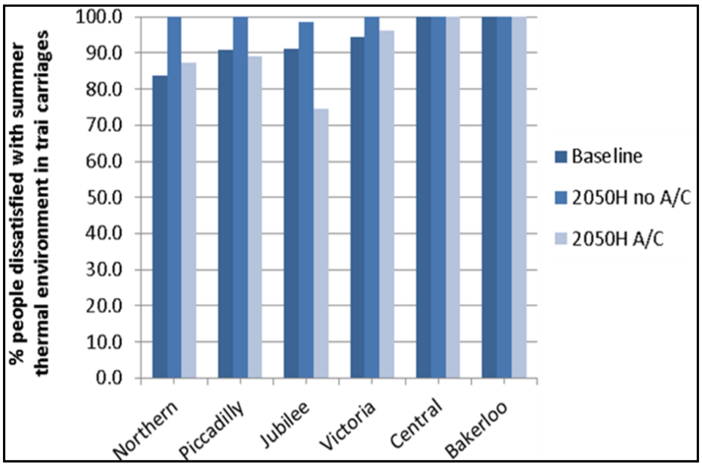

Fig. 4: The effect of air conditioning on passenger discomfort on trains (median results for the baseline and 2050 high emission scenario) assuming air conditioning provides in train cooling of 4°C

For additional information see:

- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/
- ARCADIA Factsheet 2

MODELLING THE IMPACTS OF CLIMATE CHANGE ON CITIES: ECONOMIC COSTS OF RAIL BUCKLE EVENTS

ARCADIA FACTSHEET 9

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As the effectiveness of a cities transport system is central for business, employees, and economic competitiveness damage to the system could be severe and far-reaching. In the UK high temperatures can directly damage railway lines due to buckling. This factsheet outlines a method for estimating the frequency of future buckle events under climate change. Economic costs of rail buckles are estimated and benefits of improved rail infrastructure assessed.

Context

- Railway networks are associated with an increased occurrence of rail buckling during high temperatures.
- A buckle can be defined as a track misalignment serious enough to cause derailment, which can be caused by forces produced by the metal expanding under high temperatures and by subsequent disturbance caused by a train.
- Speed restrictions are introduced when certain temperature thresholds are passed to reduce the risk of derailment.
- Theoretically, well maintained track should not be vulnerable to buckling up to ambient temperatures of ~39.3°C. However, severe buckles have been reported to occur when the maximum daily temperature is over 25°C.
- The majority of severe events occur over 27°C in London and the South-East, suggesting that track is of poorer condition.
- During the 2003 summer heatwave 137 buckle events were reported, at a cost of ~£2.5 million for repairs and delays. Extensive buckle related delays were also seen during the 2006 heatwave event.

Method

- The study provides an assessment of the number of days when one or more buckle events could occur in the study area and associated repair costs.
- Spatial temperature data from the urban spatial Weather Generator is used to facilitate an analysis of rail buckling under future climate change.
- Based on a study of historic buckle events and the corresponding temperature at the Heathrow weather station, it is assumed that buckle events could occur across London where daily maximum temperature (TMax) exceeds 27°C (fig. 1).
- The probability of one or more buckle events occurring on a day when the temperature threshold is passed is estimated based on published studies.
- The cost of repairs following a rail buckle are estimated as £10,000 per buckle.

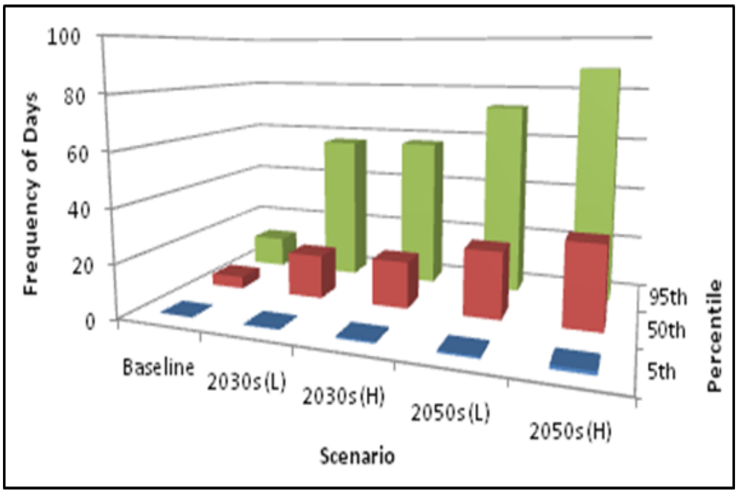

Fig. 1: The annual frequency of days which exceed 27°C at the grid cell corresponding to Heathrow for the baseline, 2030s and 2050s time periods and high (H) and low (L) emission scenarios. Results are provided at the 5th, 50th, and 95th percentile, reflecting the range of results provided by the urban spatial Weather Generator

Frequency and costs of rail buckle events

- Rail buckle events were projected to increase in frequency under all climate change scenarios compared to the present day.
- For the present day 11 to 13 buckle events are expected on average per year in the study area.
- For future time periods the study suggests that the annual number of events could increase to 56 to 70 events by the 2050s (low and high emission scenarios respectively, median results).
- Economic damages were projected to increase from £119,000 (baseline) to between £427,000 to £445,000 by the 2030s and £562,000 to £696,000 by the 2050s (low and high emission scenarios respectively, 50th percentile) (fig. 2).

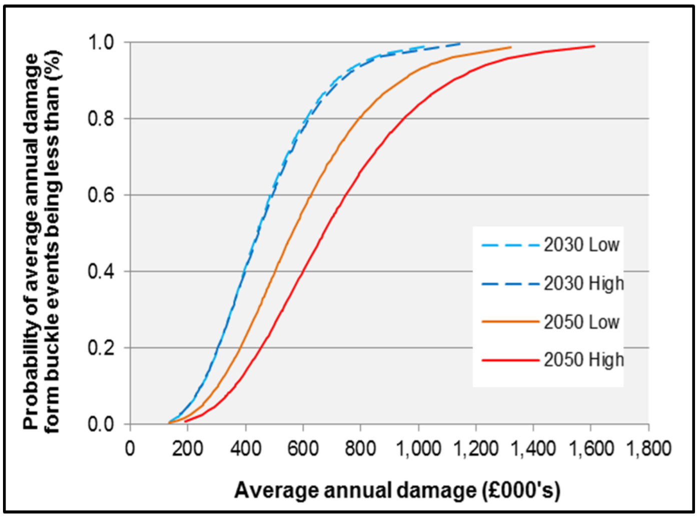

Fig. 2: Estimated average annual damage from rail buckle events for a range of climate scenarios.

Adaptation options to reduce rail buckle costs

- Given that the rail networks capacity is also set to increase there is a real need to invest and upgrade track to increase the resilience to high daily temperatures and heatwave events.
- It is stated that well maintained track should not be vulnerable to buckling up to ambient temperatures of approximately 39.3°C.
- Therefore, increased investment in the quality of track and repair and maintenance is one key mechanism to reduce risk.
- The potential cost benefits of upgraded track conditions are estimated by repeating the above methodology but increasing the TMax threshold to 31.3°C to represent moderate track conditions, and 39.3°C to represent good track conditions.
- The analysis highlights significant potential for improved track conditions to reduce buckle frequency and economic damages (fig. 3).
- Under the assumption of moderate track conditions a reduction in average annual damages of between 21 to 48% are seen in the 2030s, compared to estimates assuming poor track conditions.
- Damages are reduced by between 9 to 35% and 7 to 25% for the 2050s low and high emission scenario respectively.
- For the 2030s if it is assumed all track is of good quality no damages from buckle events are seen.
- For the 2050s good track quality results in large declines in average annual damages compared to the poor track scenario.
- For all scenarios if track conditions in the study area were of good quality then future average annual damages would be lower than the damages seen in the baseline period
- This highlights the potential economic benefits which could be gained.
- This will be particularly beneficial on key commuter routes to reduce impacts in terms of repair costs and commuter delays.

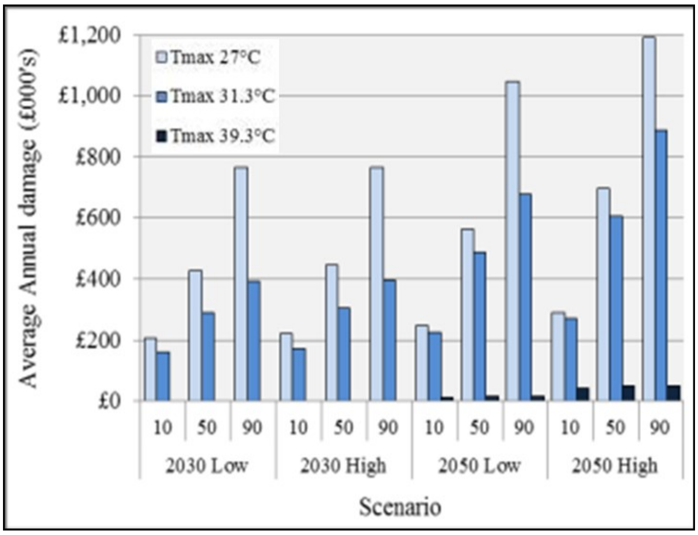

Fig. 3: Impact of track conditions on average annual damage from rail buckle events for poor track (TMax 27°C), moderate track (TMax 31.3°C), and good track (Tmax 39.9°C), for a range of climate scenarios.

For additional information see:

- ARCADIA website: www.arcc-cn.org.uk/project-summaries/arcadia/
- ARCADIA Factsheets 2 and 4

THE GOVERNANCE OF CLIMATE CHANGE ADAPTATION: A REVIEW OF LONDON

ARCADIA FACTSHEET 10

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The governance of climate change adaptation is multi-level. It cuts across different policy sectors, involves a wide range of actors, stakeholders, and interests. In the UK, its institutional landscape has been subject to a number of restructurings. This factsheet summarises key messages from an analysis of identified gaps in London's climate change adaptation strategy, led by the Mayor of London, and secondly the strategies approach to resilience.

Context

- The latest changes to the governance of climate change in the UK were introduced by the Localism Act, 2011 which abolished regional governance and withdrew the system of National Indicators, which monitored local authorities' progress on adaptation planning.
- The Climate Change Act 2008 has been retained and so has the requirement for all major government departments to produce their respective Departmental Adaptation Plans.
- In London, legislative changes in 2007 transferred the responsibility for climate change adaptation, mitigation and energy strategies from central government to the Mayor.
- The Mayor has a 'climate change duty' which requires assessing the consequences of climate change for London and preparing relevant strategies to address these.
- The Mayor also has extensive planning powers and is responsible for producing London-wide strategies for spatial planning and environment (the latter includes adaptation, mitigation and energy policies).
- Thus, the Greater London Authority (GLA) (the Mayor and the Assembly) has a uniquely powerful position in the institutional landscape of climate adaptation in London.
- This enables the GLA to coordinate the actions of other partners, notably its allied agencies − the London Fire and Emergency Planning Authority, Metropolitan Police Authority and Transport for London.
- An important part of London adaptation governance has been the production of the London Climate Change Adaptation Strategy (LCCAS). This sets out priorities and actions for managing climate related risks.

Method

- An analysis of London's climate change adaptation strategy was carried out.
- Firstly, various actors and agencies involved in climate change adaptation in London were mapped by drawing on three main sources of data: web-based information, semi-structured interviews with key actors and structured workshop discussions with project stakeholders.
- Secondly, and informed by the outcome of the first stage, a detailed content analysis of draft LCCAS was made in which the Strategy's emergency planning approach was compared with the approaches taken in other world cities.
- The analysis also focused on identifying 'gaps' in draft LCCAS with regard to its understanding of the risks and their impacts and the involvement of key actors and agencies in addressing them.
- Thirdly, the resilience approach taken by the draft LCCAS was analysed against three different understandings of resilience (engineering, ecological and evolutionary) in order to examine the extent to which the draft LCCAS has taken advantage of the social and environmental transformative potentials of climate change.

Key messages from the gap analysis of the Draft LCCA: Overarching

- Adaptation planning may need to operate within geographical regions that exceed or overlap the catchments of governing authorities.
- Existing policy mechanisms and tools may not have caught up with the powers, timelines, and rigour necessary for adaptation planning.
- Numerous partnerships and collaborations required for adaptation planning are positive for learning, co-ordination and motivation, but can also lead to fragmentations, duplications, tensions and delays.
- The private sector may have different drivers and timelines compared with the public sector and may have more stringent requirements for committing time and personnel to partnership working.
- Different organisations and regulatory regimes impose different planning periods (e.g. 5-100 years).
- Adaptation is not just a technical environmental challenge, but a social, political and normative challenge.

Key messages from the gap analysis of the Draft LCCA: London's approach

- The 'emergency' focus may lead to overlooking incremental, step-wise, adjustments to a changing climate.
- It may also lead to underuse of the communicative and place-making advantages of climate change opportunities.
- The predominant emphasis on the predictability of events focuses planning around climate risks for which evidence of likelihood is clearer, while side-lining less predictable but potentially equally harmful events.
- Greater transparency and clarity is needed about leverage of Lead Actors' nominated responsibility for the Strategy's proposed actions and consequences of failure to deliver.

Key messages from the resilience analysis of Draft LCCA

- The term 'resilience' is not clearly defined in the Strategy and shifts its meaning in different contexts.
- The Strategy's predominant approach to resilience is an engineering one.
- This contrasts with the evolutionary resilience approach, which promotes adaptive capacity building and enabling transformation.
- The transformative potential of climate change is hardly evident in the Strategy, which offers only brief glimpses of a future beyond its proposed emergency planning interventions.
- The engineering approach to resilience takes the Strategy's attention away from social processes which can enhance or diminish resilience.
- Vulnerability is framed as a descriptor of the individual's circumstances rather than an outcome of wider social processes such as social injustices and inequalities.
- The strict categorisation of actions and linearity of the 'emergency planning' approach is also contrary to evolutionary resilience which considers cities as interconnected systems with porous boundaries and extensive feedback processes which occur over multiple scales and time frames.
- In line with its 'emergency planning' approach, the Strategy is focused on responses to sudden and extreme climate events rather than on long term, small and incremental changes.
- While the Strategy is imbued with concerns over efficiency and rapidity of response, it is not strong on developing flexibility and diversity.
- Although attempts are made to examine climate impacts on the Strategy's 'crosscutting' issues, it is not clear what happens if several events occur at the same time.
- Developing and communicating a scientific understanding of the probability of events has occupied a large portion of the GLA's time and efforts and the bulk of the Strategy's contents.
- By contrast, the Strategy's understanding of consequences and impacts of events is much less informed by evidence, which has led to a lack of prioritisation of the proposed actions.

For additional information see:

- Davoudi S et al., (2011) *The London Climate Change Adaptation Strategy: Gap Analysis*. Available from: http://www.ncl.ac.uk/guru/documents/EWP44.pdf
- Davoudi S, Brooks E and Mehmood A (2013) 'Evolutionary Resilience and Strategies for Climate Adaptation', *Planning Practice and Research,* 28 (30), 307-322.