

**ENVIRONMENT**

# **CLIMATE CHANGE ADAPTING TO THE INEVITABLE?**

Institution of  
**MECHANICAL  
ENGINEERS**



**Improving the world through engineering**

This report has two parts. The first part outlines the possible climate changes which we may expect over the next 1,000 years due to continuing CO<sub>2</sub> emissions. The second part of the report outlines what engineers need to do to adapt to our future world so that we can cope with these changes.

This report has been produced in the context of the Institution's strategic themes of Energy, Environment, Education and Transport and its vision of 'Improving the world through engineering'.

**ENERGY**

**ENVIRONMENT**

**EDUCATION**

**TRANSPORT**

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## TAKING A PRAGMATIC APPROACH A MODEL EXISTENCE

The world's climate is rapidly changing and this is due, in most circumstances, to the activities of mankind. It is also almost universally agreed that a hotter world will have a considerably more energetic climate with increased frequency of extreme weather events.

Many nations of the world will be able to cope with the impacts of climatic change in the short term, albeit at considerable financial cost and with a potential increase in the loss of life. However, if global temperatures continue to rise over the next 100 to 200 years, will mankind continue to be able to cope?

In November 2009, governments from all over the world will convene in Copenhagen to negotiate a post-2012 climate change agreement – the successor to the Kyoto Protocol. The new agreement's most basic premise will be to try to limit the negative man-made effects on our climate system for future generations. In other words, the agreement will aim to reduce global CO<sub>2</sub> emissions by mitigation. However, the existing Kyoto Protocol has, to date, been a near total failure with emissions levels continuing to rise substantially.

The Institution of Mechanical Engineers, like many other organisations, has a strong belief that we need to reduce CO<sub>2</sub> levels to secure long-term human survival. However, we are also realistic enough to recognise that global CO<sub>2</sub> emissions are not reducing and our climate is changing so unless we adapt, we are likely to face a difficult future.

The report's point of departure is that we are unlikely to be far more successful at curbing our CO<sub>2</sub> emissions in the near future than we have been over the past decade or so. And even with vigorous mitigation effort, we will continue to use fossil fuel reserves until they are exhausted. However by then, atmospheric CO<sub>2</sub> levels may have risen to about 1700ppmv compared to an average of 383ppmv today.

If in the future we are to successfully adapt to changes in our environment, it is important that we not only understand the likely short and medium-term effects of climate change (25–100 years), but also the longer-term effects. However, the majority of existing climate change modelling addresses only the former with scenarios projecting to the end of this century.

Given that the majority of existing infrastructure will continue to be operational for at least another 100–200 years, this report aims to look at climatic conditions beyond 2100. Using existing climate modelling techniques, the report examines changes to our planet over the next 1,000 years. We have then considered how engineers might help adapt our world to these changes over the next few centuries.



## **THE HEAT IS ON**

The modelling techniques used for this report predict that by 2050 the world's temperature will have increased by, on average, 2°C relative to the pre-industrial climate. This is considered to be the maximum temperature increase we can allow before catastrophic and irreversible climate changes begin to occur.

The model furthers these predictions, demonstrating that even with significant global commitment to avert climate change, it could take many centuries before we can stabilise average temperatures – and that could be at up to 8°C above pre-industrial levels.

This temperature increase will have global consequences, with nearly all regions experiencing their own particular climate-related challenges.

## **THE EFFECTS ON THE GROUND**

This report examines climate change predictions for three geographical regions (UK, Shanghai in China and Botswana), chosen for their differing maritime, monsoonal and continental climates, and different stages of economic development.

### **United Kingdom**

The principal challenge for the UK will come from increased risks of flooding, resulting from a rise in sea levels and an overall wetter climate, summer droughts affecting water supplies, and high temperatures in urban areas during the summer months. It should also be noted that an 8°C worldwide average rise in temperature translates to a 7°C to 13°C rise in the UK.

### **Shanghai, China**

Shanghai, located on the Yangtze river delta, will be particularly affected by flooding issues, from both rising sea levels and an intensification of the monsoonal rains. Here an 8°C global rise is equivalent to a much larger 10°C to 12°C rise in this region.

### **Botswana**

Botswana will be particularly affected by rising temperatures, made worse by the effects from increased urbanisation in this region. Furthermore, implications for Botswana are made more severe by the fact that, as a developing economy, there may be less emphasis on climate change adaptation in deference to more immediate social and economic issues. Moreover, the 8°C global temperature rise could result in a 10°C to 15°C rise in Botswana.

## PROTECTING OUR SOCIETY THROUGH ENGINEERING

Effective adaptation to long-term changes in our climate will result in a more resilient and robust system that has the ability to cope with known factors and the flexibility to absorb unknown conditions without massive failure. Adaptive management as a response strategy will also result in more resilient systems being used efficiently and effectively.

Four areas of engineering are considered under the above climate scenarios: energy, water, buildings, and transport.

### Energy

There are implications for the longer-term positioning of large-scale energy generation sites to protect them from flooding and sea level changes. There are also considerations to be made in the positioning of renewable energy devices, as longer-term climate changes may also significantly impact site yield, particularly with regard to hydro-generation.

Regarding the distribution of energy, a fundamental move towards the greater decentralisation of energy production, via intelligent local networks, will be required. This would be coupled with a more internationally interconnected electricity grid to balance supply and demand differences (ie a European 'supranational' grid). This will, however, require international harmonisation of systems, standards, regulations, taxes and market economics.

### Water

To combat increased variability in the supply of rainwater, more resilient sources of water coupled with more efficient and robust distribution systems will be needed. Sources of water may need to include a higher proportion of underground storage and catchment, thereby avoiding excess loss from evaporation and run-off. Greater levels of desalination may also be required but this is energy-intensive, and a balance must be struck between the scarcity of water and energy consumption.

Increased water recycling will become more important and may lead to significant changes in our infrastructure, allowing for the transportation of water at different levels of purity (ie drinking or industrial production purity).

### Buildings

Buildings adaptation is perhaps the area where most consideration of future climate change has already been made. Significant gains can be made by effective master planning of urban areas to increase the utilisation of natural and artificial ventilation corridors, for both new and existing communities and developments.

However, the increasing regularity of flooding, and the impact of rising sea levels and storm surges on coastal areas, may mean that the long-term viability of entire settlements might be in jeopardy.

Indeed, a 7m rise in sea levels would impact on vast areas of the UK, including most parts of London which border the Thames ie Canary Wharf, Chelsea and Westminster, all of which would need to be abandoned.

### Transport

Finally, it is entirely probable that all current modes of transport will still be in use in 100–200 years' time, albeit in modified forms. Much of the built infrastructure will need to be assessed for vulnerability and resilience to climate change.

Master planning will need to consider alternative routes and extra capacity as well as build in redundancy, particularly in the case of rail where much of the infrastructure is sited on flood plains and coastal fringes.

Within urbanised areas, comprehensive underground mass-transport systems will be susceptible to increasing temperatures and flooding.

## RECOMMENDATIONS

Modern humans have adapted successfully to changing climates for over a 100,000 years. However, at no time in the history of our species have we lived in such large numbers and in such a complex, interconnected, interdependent and sophisticated global system; a system highly vulnerable to an altered environmental state such as climate change.

The Institution of Mechanical Engineers believes that given the evidence to date of the global community's failure to reduce CO<sub>2</sub> emissions, if human society wants to continue to thrive in its current form, it is important that we begin to put significant effort into planning adaptation on a long-term horizon.

The Institution therefore recommends that we:

- **Sink or save?** Rising sea levels and increased flooding will be the most noticeable impacts of climate change over the next few centuries. Therefore, investment needs to be made in the consideration of the long-term viability of many settlements, transport routes and infrastructure sites, planning for either their defence or ordered abandonment. Large populated areas, or locations with critical national assets such as power stations or ports, need to be a priority.
- **Be prepared.** Government should place more effort and emphasis on climate adaptation, realising that global effort on mitigation, to date, has been less than successful. This more realistic approach may be the only effective way for a nation to begin to protect its citizens without reliance on other nations to agree and implement mitigation targets. (It is our belief that in time, all nations will realise the need for mitigation, however, this will take centuries to implement.)
- **Break the fossil habit.** We need to increase investment and effort with regard to research, development, demonstration and commercialisation of new energy sources for electricity generation, such as fusion, including a significant search for as yet unknown technologies. This will help the world offset the use of fossil fuels before they become exhausted.
- **Clean up our act.** We need to invest in Carbon Capture and Storage (CCS) technology to demonstrate feasibility and ensure its commercialisation by 2030.
- **Help others.** Lead the industrialised world in taking responsibility for assisting economically vulnerable nations to anticipate and adapt to future climate change impacts in the centuries ahead.



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Whilst international policymakers try to instigate effective, widespread mitigation action that will restrict future climate change, as yet there is no evidence of it having any perceptible impact on global carbon dioxide (CO<sub>2</sub>) emissions. Instead fossil fuel CO<sub>2</sub> emissions<sup>1</sup> have grown by more than 30% since the UN Framework Convention on Climate Change was agreed in 1992, and land-use change emissions<sup>2</sup> remain substantial. Furthermore, fossil fuel emissions have accelerated from increasing at 1.3% per year in the 1990s to more than 3% per year during 2000–2006 (above all earlier projections)<sup>3</sup>.

Faced with the reality of these trends and the challenge of engineering for a future in which emissions reduction is uncertain, the Institution of Mechanical Engineers believes it prudent to assess how much the climate could change if 'business as usual' continues for as long as possible.

Reference to existing projections by the Intergovernmental Panel on Climate Change (IPCC), which stretch to the end of this century<sup>4</sup>, reveals that in 2100 the world is still warming and the climate is changing. The question therefore arises: how high will temperatures rise and what climate impacts will engineers ultimately have to respond to?

Designing and maintaining infrastructure, networks and systems that will be in place beyond 2100 poses engineers with a range of additional questions, including:

- How might post-2100 climate changes manifest into impacts?
- How far can the engineering community help society, the economy and the environment prepare for the potential impacts?
- What needs to be in place to enable the engineering community to maximise their response to the impacts, both today when working on long-term projects, and in the future?

To seek some possible answers to these questions, the Institution of Mechanical Engineers commissioned Tim Lenton, Professor of Earth System Science at the School of Environmental Science, University of East Anglia, to develop a plausible long-term global CO<sub>2</sub> emissions scenario on a centuries timescale and model the potential global warming that might result. The assumptions used in the scenario were deliberately cautious in terms of mitigation strategies, to reflect the lack of action in this area to date. Additionally, the Institution of Mechanical Engineers commissioned Ove Arup & Partners Ltd, a leading multi-disciplinary international engineering consultancy, to provide an engineering response to the output of Professor Lenton's work.

In this report the Institution brings this work together and presents an engineer's view of the adaptation challenge that may lie ahead, with particular focus on engineering for the next two centuries; a timescale over which major engineering infrastructure, networks and systems currently in place, or being built in the near future, will be expected to maintain operational integrity.



**FOSSIL FUEL CO<sub>2</sub> EMISSIONS HAVE GROWN BY MORE THAN 30% SINCE 1992.**

# THE CO<sub>2</sub> TIMELINE

A long-term global CO<sub>2</sub> emission scenario was constructed which assumes that 'business as usual' is maintained for as long as possible and then, following a climatic trigger, things change at a plausible rate. The future fossil-fuel emissions scenario was constructed using a mathematical approach involving a simple formula<sup>6</sup>, and a number of defensible assumptions.

## Long-term CO<sub>2</sub> Emissions Scenario

It begins in the year 2000 with CO<sub>2</sub> emissions of 7GtC per year, which then increase at the current average rate for the last 25 years of 1.9% per year. Emissions continue to increase at this rate until 2050, when effective global mitigation is assumed to begin.

We argue that this would be provoked by reaching 2°C global warming in the 2040s, causing "dangerous anthropogenic interference in the climate system" including the passing of some climate tipping points<sup>7</sup>.

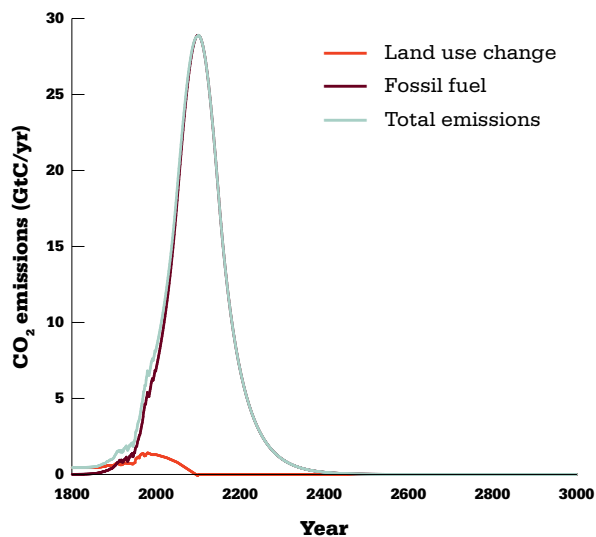
Indeed, organisations such as the European Union believe that an increase of 2°C relative to the pre-industrial climate is the maximum acceptable temperature rise to prevent uncontrollable and catastrophic climate change. It would be at this point that we would reasonably assume that meaningful and effective international action would begin.

The scenario then assumes that it takes 100 years to globally transform the means of energy provision and achieve a maximum rate of reduction in CO<sub>2</sub> emissions. Initially, actions might take the form of a step increase in the deployment of renewable energy systems, fourth-generation nuclear power stations, carbon capture and storage technology<sup>8</sup> and electric-powered transportation. In parallel with this a dramatic research, development and deployment push for radical non-fossil fuel-based energy alternatives, such as fusion and other as yet undiscovered potential sources would be undertaken. Given the anticipated scale of global energy demand by circa 2050<sup>9</sup>, we argue that a timescale of 100 years for such a transition is plausible.

During this transition, the deceleration of emissions is assumed constant. Following this period, a maximum rate of reduction in CO<sub>2</sub> emissions is then sustained until the 4000GtC of conventional fossil-fuel resources<sup>10</sup> are all ultimately used up.

Mathematically the problem is fully constrained and the assumed fossil-fuel resources dictate that emissions must reduce at a rate of 1.9% per year in 2150 and thereafter. A 1.9% per year decrease in emissions is economically plausible in that it demands other sources of energy to be able to increase at the rate fossil-fuel usage has done over a 25 year average.

The resulting CO<sub>2</sub> emissions scenario is shown in Figure 1. Up to 2100 it is similar to the IPCC Special Report on Emissions Scenarios<sup>11</sup> (SRES) A2 scenario. Emissions peak in the year 2100 at 28.9GtC per year and decline thereafter. Current conventional fossil-fuel reserves total<sup>12</sup>, about 1500GtC so, in common with IPCC SRES A2, our scenario implies that increased fuel prices and/or technological improvements will lead to increased fossil-fuel extraction.

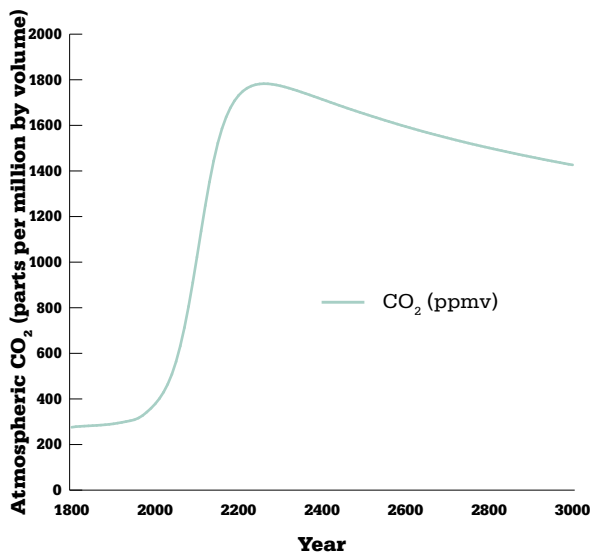


**Figure 1:** The long-term CO<sub>2</sub> emissions scenario constructed in this work, and used as input to the GENIE-1 model.

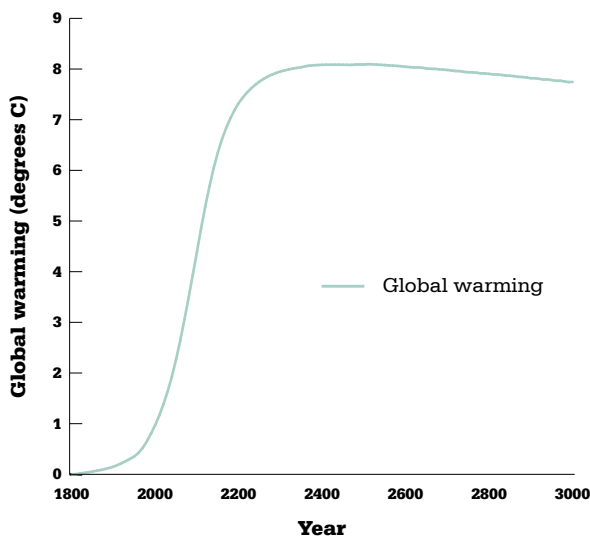
## FOOTNOTE

Historical fossil-fuel emissions<sup>1</sup> (totalling 282 billion tonnes of carbon or GtC) and land use change emissions<sup>2,5</sup> (totalling 147GtC) were taken from published estimates, and future land-use change emissions (totalling 71GtC) follow a published scenario<sup>5</sup>.

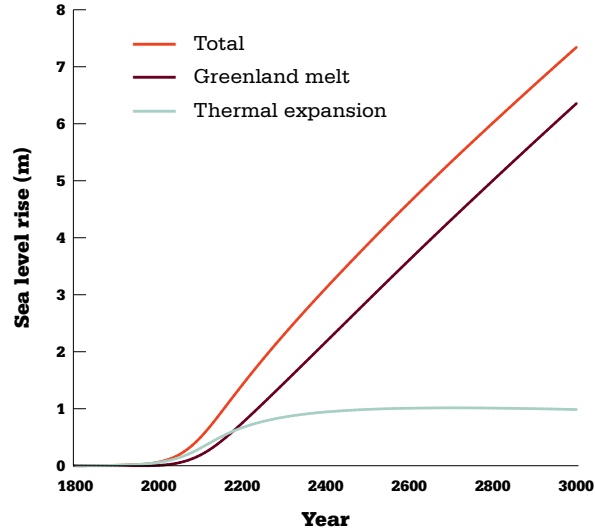
To project long-term changes in atmospheric CO<sub>2</sub> concentration and the global climate, the CO<sub>2</sub> emissions scenario was used as an input to the GENIE-1 (Grid-ENabled Integrated Earth system) model<sup>13</sup> (see box on p9), with the results shown in **Figure 2a-c**. The output from the model reveals the following.



**Figure 2a:** Atmospheric CO<sub>2</sub> concentration



**Figure 2b:** Global temperature change



**Figure 2c:** Sea level rise

## HISTORICAL

GENIE-1 does well at reproducing the historical rise in atmospheric CO<sub>2</sub> from the pre-industrial level of 280 parts per million by volume (ppmv). The model predicts 354ppmv in 1990 in agreement with observations, and 373ppmv in 2000, about 4ppmv above observations.

The predicted global warming to present (for 2001–5 relative to 1850–1899) is 0.9°C, at the upper end of the range of the IPCC estimate of 0.57–0.95°C (it is a little high partly because sulfate aerosol cooling is not included, but this factor is expected to decline in future).

As with most climate models, predicted sea-level rise is well below observations because the melting of inland ice (other than Greenland) is not included. This means that future sea-level rise is also underestimated, especially on the century timescale, because many small ice caps (in mountainous areas) are expected to be lost this century<sup>4</sup>.

## 2000–2100

Atmospheric CO<sub>2</sub> reaches double the pre-industrial level (560ppmv) in 2050 and global warming exceeds 2°C above the pre-industrial in the 2040s. Consequently some tipping points may be passed by mid-century<sup>7</sup>. In 2100, emissions reach their peak of 28.9GtC per year, atmospheric CO<sub>2</sub> has exceeded 1000 ppmv and global warming is 4.4°C above pre-industrial or 3.4°C above our present temperature levels (this is in the middle of the range given by the IPCC for its A2 scenario<sup>4</sup>).

Thermal expansion of the ocean is estimated to contribute a 0.31m to sea level rise, and melting of the Greenland ice sheet 0.19m, giving a total of 0.5m (or 0.45m since the late 20<sup>th</sup> century) at the upper end of the IPCC A2 scenario range<sup>4</sup>. This is likely to be an underestimate because the melting of smaller inland ice caps has been excluded.

## 2100–2200

By the end of the first decade of the 22<sup>nd</sup> century, emissions are declining, but atmospheric CO<sub>2</sub> has reached four times the pre-industrial level (1120ppmv) and is still rising. Global temperature is changing at its most rapid rate of 0.46°C per decade, and shortly after, in the 2110s, global warming reaches 5°C above pre-industrial levels.

As the 22<sup>nd</sup> century progresses, the global temperature continues to rise but at an ever decreasing rate. Average temperatures pass 6°C above pre-industrial levels in 2140 and 7°C in 2180. By the year 2200 the temperature is increasing more slowly (0.14°C per decade) than at present (0.17°C per decade).

Sea level rise is projected to be greater in the 22<sup>nd</sup> century than in the 21<sup>st</sup>, due to ongoing melt of the Greenland ice sheet. It reaches 1.42m in 2200 and is rising at an almost constant rate of 0.09m per decade.

## 2200–3000

Atmospheric CO<sub>2</sub> peaks in 2250 at 1780ppmv, by which time mitigation activity and dwindling fossil-fuel reserves have caused emissions to fall to 2.5GtC/year, about a quarter of their value today. By this time, 4364GtC (equivalent to 2050ppmv) have been added to the atmosphere by human activities and an additional 3195GtC (1500ppmv) are present there.

The ocean has taken up about 1200GtC but the land has become a source of about 200GtC – mostly from soils. The combination of a weakening of the ocean carbon sink, due to a change in the deep overturning circulation of the Atlantic, and the switch of the land from a carbon sink to a carbon source, contributes to the high peak in CO<sub>2</sub> and global warming.

In 2250, global warming is 7.75°C above pre-industrial levels and the temperature increases slowed to 0.06°C per decade. Temperature continues to rise because the ocean is still slowly heating and there are ongoing positive feedbacks in the climate system, including the loss of sea-ice and land snow cover.

By the year 3000, atmospheric CO<sub>2</sub> has dropped to 1430ppmv thanks to the uptake of an additional 940GtC by the ocean. However, global temperature has cooled only slightly, having peaked above 8°C, and is still 7.75°C above pre-industrial levels.

Sea levels have risen by more than 7.3m and there is little left of the Greenland ice sheet, which is still melting. The Atlantic overturning circulation remains fundamentally altered.

## THE MODELS USED IN THE WORK

GENIE-1 is an Earth system model<sup>13</sup> of intermediate complexity, comprising a three-dimensional ocean, simplified (energy and moisture balance) atmosphere, sea-ice and land surface coupled to a fully interactive global carbon cycle including simple representations of vegetation, soil and the marine biosphere. The surface of the world is divided into 36 × 36 grid cells on an equal area (longitude-sine of latitude) grid, with 16 vertical levels in the ocean but only one in the atmosphere.

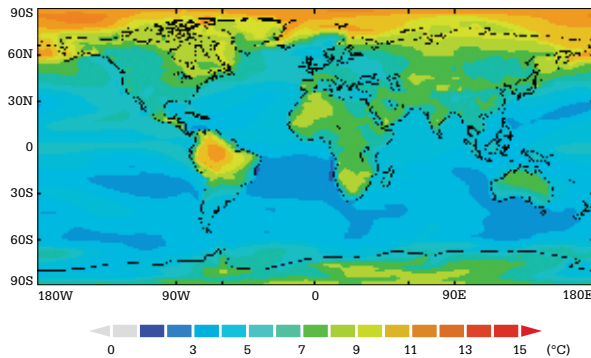
HadCM3L is a full complexity climate model, comprising three-dimensional general circulation models of the ocean and atmosphere, coupled to sea-ice and land surface models, all with a horizontal resolution of 3.75° × 2.5° on a longitude-latitude grid, with 19 vertical levels in the atmosphere and 20 in the ocean. The simulations analysed here were run by D. J. Lunt at the University of Bristol. The parent model<sup>14</sup> HadCM3 differs in having a higher horizontal ocean resolution of 1.25° × 1.25°.

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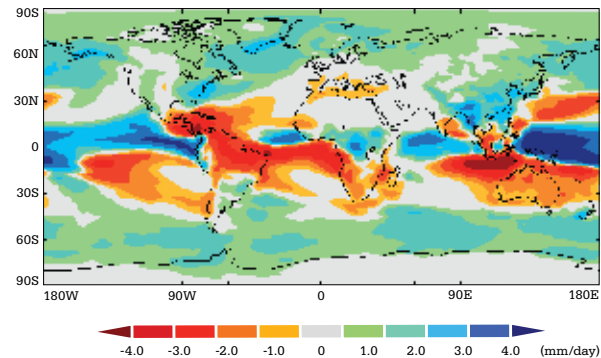
To examine the long-term future climate change scenario in more regional detail, and to allow the engineering response to be considered, two time horizons were chosen: early in the 22<sup>nd</sup> century when global warming has reached roughly 5°C, and the middle of the 23<sup>rd</sup> century when global warming is approaching the anticipated maximum of 8°C. Existing output from the Hadley Centre model HadCM3L (see box on p9) with corresponding levels of global warming were identified and compared to the control runs HadCM3L and HadCM3 (with a higher ocean resolution) to determine the regional climate changes.

The pattern of annual average temperature and precipitation change across the 5°C and nearly 8°C warmer HadCM3L worlds is shown in **Figure 3a-d**. The land is seen to warm more than the ocean and the high latitudes more than the low latitudes. Drying is pronounced in Mesoamerica, Amazonia, the Mediterranean, Southern Africa, Australasia and much of India. Southeast Asia and the boreal region get wetter.

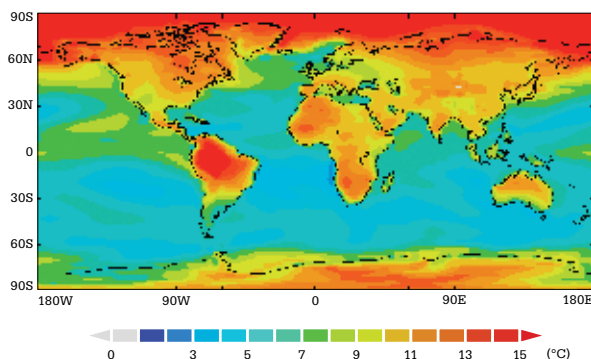
**Figure 3a:**  
Surface air temperature change in a world 5°C warmer



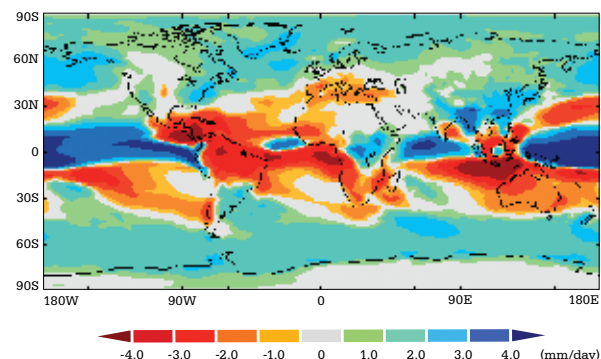
**Figure 3b:**  
Precipitation change in a world 5°C warmer



**Figure 3c:**  
Surface air temperature change in a world 8°C warmer



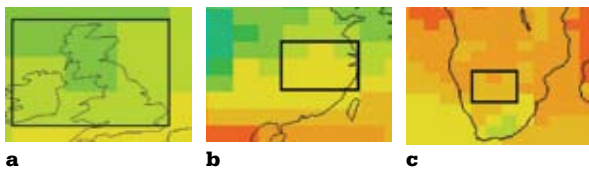
**Figure 3d:**  
Precipitation change in a world 8°C warmer



Three regions were chosen to illustrate what happens in nations/regions with different climate regimes, which are at different stages of economic development and will require differing engineering responses to the climate changes:

- The United Kingdom is an example of a fully developed nation with established engineered infrastructure, networks and systems, that will be expected to be operational long into the future, and economic and indigenous technical capability to build adaptive capacity. It has a maritime climate.
- The Shanghai area of Eastern China is an example of a rapidly developing region, where newly engineered infrastructure, networks and systems will be expected to be operational for hundreds of years, and that will have the economic and indigenous technical capability to build adaptive capacity. It has a monsoonal climate.
- Interior southern Africa including Botswana is an example of a region with little existing or developing engineered infrastructure, networks and systems, and lacks economic and indigenous technical capability to build adaptive capacity. It has an inland continental climate.

Monthly data for surface air temperature, precipitation (rain plus snow) and wind speed were analysed, initially at the level of model grid boxes, and then averaged over 3×3 grid cell regions (**Figure 4**), which have a horizontal resolution in order of 1000km. Wind strength is not discussed as it generally showed no significant trends. For further details on this IMechE commissioned report, visit: [www.imeche.org/environment](http://www.imeche.org/environment)



**Figure 4:** The three regions, each comprising nine grid cells of HadCM3L/HadCM3.

**a:** Most of the United Kingdom and Ireland  
(9.375°W-1.875°E, 51.25°N-58.75°N)

**b:** Eastern China around Shanghai  
(110.625°E-121.875°E, 26.25°N-33.75°N)

**c:** Interior southern Africa including Botswana  
(16.875°E-28.125°E, 18.75°S-26.25°S).

## UNITED KINGDOM

The pattern of climate change across the UK is generally consistent with the picture presented for this century by the UK Climate Impacts Program (UKCIP)<sup>15</sup>, but amplified by the greater magnitude of projected global change beyond the century timescale.

### Temperature

The summer warms more than the winter, an increased seasonal contrast which is accompanied by a shift of peak summer temperatures later in the year. In an 8°C warmer world, about half the summers will have a mean monthly temperature above 28°C for one or two months. The greatest summer warming, of up to 12°C, occurs in the south. However, greatest winter warming, of up to 9°C, is in Scotland due to loss of snow cover.

### Rainfall

Summers in the UK will be drier with southern regions being most affected. In winter, the UK would experience higher levels of precipitation and overall the nation will become wetter.

### Sea Levels

The 2m sea level rise projected to occur in the latter half of the 23<sup>rd</sup> century would inundate significant areas of the UK including the Norfolk Broads and parts of London (**Figure 5a-b**), if no adaptation effort is made to prevent it. The sea level rises projected could significantly redraw the map of the UK and threaten the entire viability of London as well as key ports and power station sites such as Sizewell in Norfolk.



London at today's sea levels



London with a 2m sea level rise



London with a 7m sea level rise

**Figure 5a:** Flooding that would occur due to 2m and 7m global sea level rise in the Thames estuary, assuming no adaptation in the form of sea defences. In our 'business as usual' projection 2m is reached around 2250 and 7m toward the end of the millennium.



East Anglia at today's sea levels

East Anglia with a 2m sea level rise

East Anglia with a 7m sea level rise

**Figure 5b:** Flooding that would occur due to 2m and 7m global sea level rise in East Anglia, assuming no adaptation in the form of sea defences. In our 'business as usual' projection 2m is reached around 2250 and 7m toward the end of the millennium.

## EASTERN CHINA

China covers a vast area with a variety of climates. The report focuses on the region around and inland from Shanghai.

### Temperature

The most significant change will be in the summer months when the mean temperature will exceed 28°C for typically three to four months each year in a 5°C warmer world. In an 8°C warmer world, this will average five months each year.

### Rainfall

Overall the area will become wetter, particularly in spring with an intensification of the monsoon. Summer rainfall also intensifies to the south of our area of analysis.

### Sea Levels

A 2m sea level rise (corresponding to the late 23<sup>rd</sup> century) has a modest effect but 7m (corresponding to the end of the millennium) threatens to inundate the whole region around Shanghai (**Figure 6**).

## BOTSWANA

Warming in southern Africa is greatest in the continental interior, which also gets drier, consistent with century timescale projections. It is also one of the few regions where precipitation projections across different models generally agree.

### Temperature and Rainfall

Warming is greatest in southern hemisphere autumn (our spring), reaching 13°C to 15°C in an 8°C warmer world, which is at least 10°C to 11°C warmer in this region throughout the year. The number of months in the year where the mean temperature exceeds 28°C increases from usually zero in the pre-industrial climate to three to six months in the 5°C warmer world and typically eight months in the 8°C warmer world.

Prolonged winter drought conditions occur in both 5°C and 8°C warmer worlds and most of the year is typically drier.



Shanghai at today's sea levels

Shanghai with a 2m sea level rise

Shanghai with a 7m sea level rise

**Figure 6:** Flooding that would occur due to 2m and 7m global sea level rise in the Shanghai region, assuming no adaptation in the form of sea defences. In our 'business as usual' projection 2m is reached around 2250 and 7m toward the end of the millennium.



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**A 7M SEA LEVEL RISE  
WOULD THREATEN  
TO INUNDATE THE  
WHOLE REGION  
AROUND SHANGHAI**

# ADAPTING TO A NEW WORLD (ENGINEERING CHALLENGES)

Changes in climate conditions will present engineers with a wide range of challenges. These challenges relate to how existing infrastructure and buildings may need to change to function under a new climate system, and how new systems can be designed and built to function under a different climate, thereby helping the world to adapt.

It is acknowledged that modelling climate changes to dates far into the future will include uncertainty and the scenarios reported in this report should be considered as possible outcomes rather than a definite prediction of what will happen. As such the discussions contained in this section onwards on adaptation are in response to the general trends indicated in the modelling rather than the precise details of the data. By taking this approach, confidence in the applicability of the results will be higher.

Whilst this report is primarily focused on possible engineering design changes that will increase the resilience of infrastructure systems and components, it is important to place these discussions within the wider context of the full range of possible effects of climate change and population strains.

The population of the world is predicted to rise to 8.9 billion in 2050 (from 6.1 billion in 2000) before stabilising<sup>16</sup>. This will place increased strain on resources and will obviously have a large impact on how people live.

In combination with population pressures is a possibility that increasingly large tracts of currently inhabited land will be unable to sustain significant populations due to a number of factors such as sea level rise, increased temperature or drought. This may result in large-scale population migration, placing even more pressure on the temperate regions of the world. These issues will have profound effect on the methods used to provide food for the population and associated distribution systems.

Although we have constructed and analysed a long-term 'business as usual' climate change scenario, it is questionable whether business-as-usual could continue under the climate changes projected. Thus, it is unclear whether a globally 8°C warmer world could ever be reached. The disruption to societies on the way there would clearly be substantial and the habitability to humans of at least one of the regions we focus on (Botswana) is seriously compromised.

The effects these and many other issues will have on societal structures and behaviours will be many and varied. The incorporation of these effects is beyond the scope of this report. Their influence is, however, recognised as being as important, if not more so, than any innovations the engineering community could envisage. Similarly, the possible benefits that might result from technological advances or financial changes cannot be qualified.

For this report we have focused on four key areas which are crucial for our society's continued development and in which engineers can contribute significant thought leadership – energy, water, built environment and transportation.

## ENERGY

There are many assumptions that are required when discussing projections at these timescales, probably none more pertinent than the envisaged method of energy transfer. If the dominant energy carrier were to change from electricity to, for example, hydrogen, our future energy infrastructure would be almost unrecognisable. For the purposes of this report we are assuming that the energy generation and distribution network will remain primarily based on electricity.

It is assumed that renewable energy generation will have a significant role in the years under consideration, along with a probable increase in generation from nuclear plants. Under the emissions scenario that results in the predicted climates being considered, there may also be a significant proportion of energy being provided by coal, particularly in the near to medium terms.

This is particularly true of Botswana and China, which have abundant coal deposits and are currently building power stations to increase the reliability of their energy supply and to cope with dramatically rising demand. With the development of carbon capture and storage (CCS) technologies<sup>17</sup>, coal-fired power stations could continue to contribute to the world's energy supply and therefore require adaptation methods.

### Generation

Of the more traditional sources of energy, power stations are initially designed for a working life of about 50 years and so would not necessarily need to be considered at these timescales. There is the possibility, however, for significant life extensions in the future, resulting in an increased need for a focus on the adaptation of the design. Current locations may also be used repeatedly for future facilities which may require adaptation measures.

Facilities with design lives that reach into the next century, albeit with significant refurbishment, will need to incorporate effects such as rising sea levels and an increased probability of flooding. This issue is exacerbated by the fact that power stations, be they fossil fuel-fired or nuclear, have high cooling requirements and are therefore sometimes placed near the coast or on flood plains.

Flood risks can be minimised by the raising of the level of the facility whilst keeping its location. Issues such as these are particularly relevant to China, which is planning on massively expanding its nuclear-generation capability over the next two decades<sup>18</sup>. However, in the UK, nuclear sites such as Sizewell, which is based on the coastline, may need considerable investment to protect it against rising sea levels, or even abandonment/relocation in the long term.

Decentralised generation will reduce the need for large generation facilities located in areas of risk and localised infrastructure will require less cooling power. With the increased role of renewable energy sources within decentralised networks, the effect of climate change on the outputs of the various energy types should be addressed. At the larger scale, the changes in precipitation levels could affect the efficiency or even viability of hydro-electricity schemes.

Considering smaller-scale generators, whilst average wind speeds returned by the climate models seem to be largely similar to those seen today, there are effects that cannot be resolved when modelling at these timescales. For example, increased cloud cover could lead to reduction in the energy yield from photovoltaic and solar thermal panels. Whilst the working life of these technologies means that individual panels will be replaced, there are implications for the long-term planning of the energy supply mix.

## **WATER**

### **Distribution Network**

Applying the principles of resilience to energy generation and distribution infrastructure will be made more challenging by the very nature of the sources of power.

Renewable energy is intermittent and largely uncontrollable in its availability. Addressing this intermittency may in fact help to create a more resilient generation and distribution network as a matter of course, thereby making it more adaptable to climate change.

Providing uniform supply from generation capability that contains a large proportion of renewable power will require more large-scale interconnection between countries, which will require increased international harmonisation of standards, regulations, policies and taxes.

Unfortunately, the transmission of power over large distances currently results in higher transmission losses. Therefore, a dual-layer network is needed with smaller lower-voltage networks that can operate with minimal transfer losses embedded into a larger national and international system. Local distribution networks will also need to become more intelligent and not rely on centralised balancing of generation and supply.

To cope with increasingly volatile weather, the relocation of transmission lines to under the ground may be appropriate in some areas. However, whilst the probability of the supply being interrupted is lessened, the time taken to fix any faults may increase, possibly leading to a less resilient network. Climate change may also impair the cooling provided by wet ground to underground cables (eg Auckland blackout in New Zealand in 1998).

Assuming that energy will become a scarce commodity in the future opens up the debate as to whether there will be a tariff structure that distinguishes between essential and non-essential uses. Currently market economics drive the distribution of energy and this may not be a suitable mechanism for the determination of energy share in the future. This issue may become even more important with the increased international connection of the energy grid resulting in a more uniform global price for electricity.

The worlds under consideration, both in 2100 and 2250, are predicted to have a much more energised atmosphere than today, leading to larger variations in all aspects of the climate. This will lead to an increase in both extreme rainfall events and periods of minimal average rainfall.

Botswana may be dramatically affected, with increasingly unreliable rains leading to further desertification, thereby making agriculture even less viable. One way of reducing water requirements would be to increase the levels of food imports, and therefore also the water 'embodied' in the food, from regions with more rainfall. Agriculture is the largest user of water globally.

To combat this increased variability in the supply of rainwater, more resilient sources will need to be coupled with a more efficient distribution system and, even more fundamentally, significant efforts in the area of demand reduction.

### **Sources**

Water from precipitation is a finite resource that has variations over time that often do not coincide with levels of demand. The use of more water than is being replaced is inherently unsustainable in the long term but in the short term, the use of reserves may be necessary to continue supplies through periods of drought. More accurate prediction models will therefore be required to allow the combination of sources to be managed more effectively.

The storage of collected rainfall above ground is subject to significant losses through evaporation, a consequence that will only increase with rising temperatures. A major alteration to our water supply strategy may be needed, with an increased proportion of our water being taken from groundwater sources and underground stores to avoid losses through evaporation.

However, the predicted increase in volatility of rainfall could have adverse effects on the amount of groundwater available. As the rate of precipitation increases, the proportion of water that runs off the surface of the land increases, as soils can absorb water only at a certain rate, leading to a reduction in water in aquifers.

If precipitation does not provide sufficient water, then an alternative option is the desalination of sea-water. This is not a new technology but it is at present energy intensive. In a world where both energy and water are highly valued scarce resources, a balance may have to be struck as to the relative importance of energy and water levels. Energy-free solar desalination is a possibility although it does require space, a commodity that may be equally as scarce as water or energy.

The utilisation of an increased spectrum of sources will lead to a more resilient supply, as each source will have a different response to variations in rain intensity. An increased reliance on locally collected water will also reduce demand from regional supplies, with developments being as close to a self-sufficient closed-loop system as possible.

### **Distribution Network**

Past experience suggests that water distribution networks have a very long working life. They therefore have to be able to adapt to a changing climate in the short, medium and long terms.

As the water distribution network is progressively replaced over the coming decades, the largest improvement to the efficiency of the system can come through the installation of pipes that are less likely to leak (in the UK currently 22% of water is lost through leakage<sup>19</sup>). More comprehensive monitoring and metering systems can also assist in quickly detecting leaks.

To increase the resilience of a local water system to allow it to adapt to climate change, there needs to be increased flexibility in the sources of water. Local regions should be interconnected to allow the transport of water between them.

Botswana already relies on an 'N-S carrier pipe' to transfer water to the drier south, and China is currently building a massive network of canals and pipes to transfer water to alleviate shortages in the North. However, a significant proportion of the Chinese network is above ground, leading to increased losses from evaporation as temperatures rise.

In the UK, the interconnectedness of local networks may become even more important if an increased proportion of water is drawn from ground sources. The availability of groundwater in a region is very dependent on the underlying geology, meaning that some regions have naturally more abundant groundwater reserves than others. Local sources should take priority, however, as the movement of water over long distances is energy-intensive.

The current water infrastructure is based around the principles that water of a single level of high purity is delivered and waste water of an assumed high level of toxicity is removed. On a local level this is already being addressed with the installation of grey-water recycling system, recognising the fact that waste water from one process can be sufficiently cleaned locally to be used as the source water for another process.

The extension of this principle to include some of the national network could lead to a dual-purity grid where potable water is supplied only where it is needed and lower-purity water incorporating waste water from certain processes is supplied to industry or for irrigation uses. Whilst this would be difficult to implement for the entire national distribution system, on a local level it would be easier, particularly if it is incorporated into new developments.

This issue of re-using waste water is being addressed on a large scale in Singapore, with grey- and black-water being put through an initial level of purification before being re-introduced into the reservoirs to be added to the potable water supply in a process known as Planned Indirect Potable Use<sup>20</sup>.

## BUILT ENVIRONMENT

Projections for climate change have direct implications on building design and operation and as such the building sector is perhaps one that has been considered most with regard to climate adaptation. Using the UKCIP02<sup>15</sup> predictions a number of existing publications discuss the implications of climate change on buildings:

- CIBSE Guide L – Sustainability
- CIBSE TM36: Climate change and the indoor environment: impacts and adaptation
- Greater London Authority: Adapting to climate change: a checklist for development: Guidance on designing developments in a changing climate
- Hacker JN, Belcher SE and Connell RK: Beating the heat: keeping UK buildings cool in a warming climate

These existing publications all focus on adaptations required to withstand possible future climate scenarios outlined in the UKCIP02 report which extends to 2080. The predictions in the climate change model we are considering in this report extend to the year 2250 and are considerably more stark than those predicted at 2080.

### Master Planning

Well designed master plans will be instrumental in ensuring comfortable towns and cities in future extreme climates. The understanding of street layout, building orientation, massing and location is critical in minimising overheating in and around buildings, and reducing risks of flooding. Lessons can be learnt from developments in existing hot climates and recent advances in the understanding of zero-carbon master planning from projects such as Dongtan in China.

The legacy infrastructure of existing towns and cities is likely to pose more of a problem than new developments and will require forward-thinking high-level strategic master planning to meet future climate changes. Some key issues might be:

- Consider the viability of adjusting street layouts to respond to prevailing winds to maximise ventilation and cooling.
- Avoid locating new developments on flood plains, allow sacrificial land.
- Design flood defences into any new infrastructure.
- Consider orientation and massing of new buildings to maximise the potential for self-shading and cooling.

The change in conditions caused by the Urban Island Heat Effect will serve to make the local climates in and around towns and cities more extreme than surrounding rural areas. Master planning can be used to reduce these effects, particularly by affecting the height of buildings and street orientation to allow winds to carry heat out of the building structures.

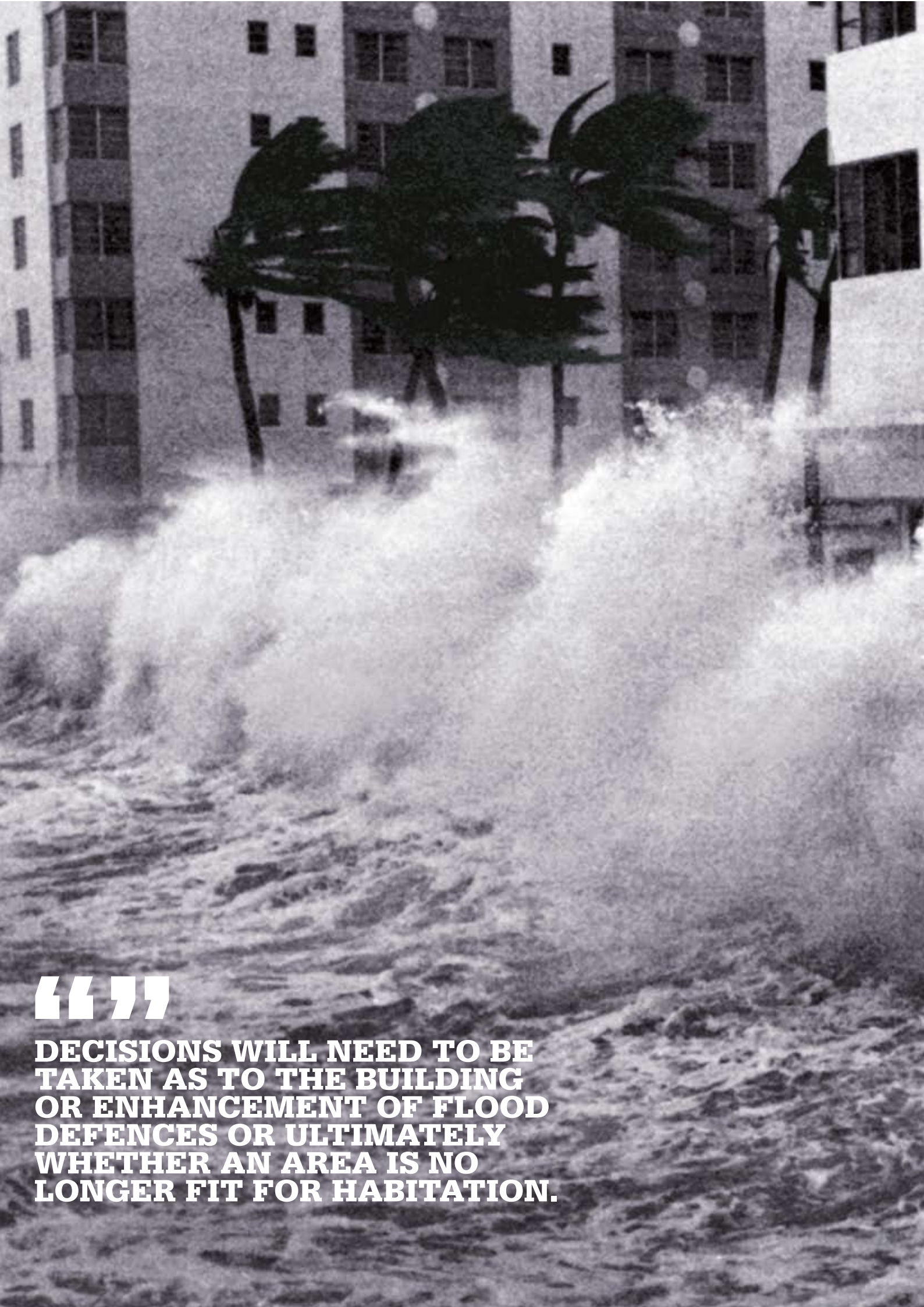
On a wider scale, the increased pressure from rising sea levels and the possible increase in severity of storm surges combined with an increase in flooding from extreme precipitation events will lead to the viability of entire settlements being threatened.

Decisions will need to be taken as to the building or enhancement of flood defences or ultimately whether an area is no longer fit for habitation. Issues such as these may well be influenced by the insurance industry weighing up the risks of providing policies to homes and businesses in these areas.

Initially these decisions will involve small outlying areas, but the situation will gradually evolve to require the consideration of these factors with regard to more major towns and cities around the globe such as London and Shanghai.



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## Buildings

Whilst current new commercial buildings are generally designed with a lifespan in the order of 50 years before they will need either replacing or major refurbishment, there is a large proportion of the current building stock, particularly iconic or residential buildings in the UK, that is significantly older.

It is projected that approximately two thirds of the homes we will be living in the year 2050 have already been built<sup>21</sup>. There is therefore a need for a comprehensive programme of adaptation required on the current housing stock. In contrast, the lifespan of a typical Chinese residential building currently stands at less than 30 years. Increased regulation of the building industry is required to increase the quality of buildings delivered.

Though current buildings may need refurbishment prior to the timescale considered here, some components may remain, such as the structural frame. It is because of this that it is appropriate to consider adaptation and flexibility within the major building components to cope with a world in 2110 with an average temperature rise of 5°C. This will see a major change in architectural styles and building geometries, particularly as low-energy buildings become the norm.

Resilience to extreme weather events will also need to be reviewed. The current peak design data used by engineers when designing internal heating, ventilation and cooling solutions for buildings will need to be reviewed to reflect future scenarios. The structural design parameters will also need updating regularly to cope with predictions for increased flooding, subsidence, effects of heat on materials and resistance to rain penetration.

Resilience to flooding is already being addressed in many countries. Flood defence is a major climate risk consideration expected to be exacerbated by climate change as a result of more intense precipitation events, sea-level rise and intense storms.

## TRANSPORT

It is assumed that all the modes of transport in use today will continue to be available, albeit in radically altered forms. There will undoubtedly be considerable change in the distribution of modes of transport but this is almost irrelevant as any level of use of a mode of transport will mean that an infrastructure is necessary.

Considering the changes to the transport network is perhaps the most difficult of the sectors to address. Energy, water and buildings are all vital to life, with set minima that levels cannot drop below. Of the sectors being considered, transport is the one most susceptible to societal and behavioural change. Physical transportation levels also have the possibility of being significantly affected by the increased capability of the communications network – the development of which is impossible to even imagine over these timescales.

### Transport Network

Whilst the design life of some individual components of the transport infrastructure may be less than the timescales being considered in this report, there is still significant adaptation needed. Even if components are replaced, the routes taken by major transport connections are unlikely to be significantly changed, meaning that cuttings and embankments will remain in use, requiring alterations and improvements to cope with increased flooding.

Rail routes in particular can be susceptible to flooding due to their relation to the geography that they pass through. In the UK, many run along river valleys where they were originally constructed to reduce gradients<sup>22</sup>.

The effect of this flooding is increased due to the degree of equipment located at track level. Particularly vulnerable is the track circuit system that currently forms the basis of most signalling systems. Adaptation strategies could include altering the signalling system to rely on trains communicating their position, as opposed to tracks sensing their presence, thereby eliminating the reliance on track-side equipment. An alternative approach would be to increase the levels of drainage installed on vulnerable areas of track.

Perhaps the most effective way to increase the resilience of a transport system is by an increase in capacity. If a system is operated near its absolute limit, any reduction in efficiency of a part of the system causes dramatic knock-on effects and the rail network in the UK is approaching the limits of its capacity, at certain times of the day, in an increasing number of places<sup>23</sup>. An example of this ripple effect occurred during extreme temperatures in August 2003, when buckling rails caused speed restrictions to be put in place along a number of stretches of track. Due to the lack of spare capacity at peak times, the restrictions had a major impact on the entire network.

An increase in resilience to unknown factors can also be reached by increasing the efficiency with which any breakages in the network are dealt with. For the rail network, this could be achieved by the increased provision of alternative routes, taking into account the electrification of the routes to allow use by all types of train. For a road network, this could manifest itself, for example, in an increase in communications technology that allows road users to bypass problem areas with as little disruption as possible.

Bridges carrying transport networks across shipping lanes may have to be designed with an increased height to take into account rising river and sea levels, as has been seen where rises in the Huang Pu River have been combined with the land subsidence in Shanghai to increase potential problems.

## **Connection Nodes**

Train stations will need to be adapted to changing conditions, with the factors that affect them being similar to those affecting other buildings. Stations may prove easier to adapt to the climate in some ways; for example, their high ceilings and open plans may make them less susceptible to overheating and easier to naturally ventilate.

A more significant problem will be the effect of flooding and increased temperature on underground mass transit systems, which will become more important components in the transport system as a whole due to the increasing population of cities.

Of the locations being considered, London has the oldest underground system in the world, having begun operation in the 1860s, and Shanghai's is amongst the youngest and fastest developing.

London underground currently removes 30 million litres of water every day<sup>24</sup> and with increases in sea levels and flooding events, this requirement is set to increase. During the summer months, temperatures already reach very high levels and the issue of cooling the trains and platforms has much focus. Whilst the rolling stock is not suitable for consideration under the timescales of this report, the fundamental issue will remain that air conditioned trains will eject heat into the tunnel network.

Along with increased ventilation, the use of the local groundwater to cool the tunnel and platform network currently seems the most feasible. This strategy will need to be considered against the climate change scenarios to determine whether this method will be able to absorb the increased heat loads from a network with a higher ambient temperature. Combined with this, reductions in the heat load could be investigated, such as regenerative braking and more efficient drive motors.

## **Enabling the Engineering Profession**

The engineering profession is an important stakeholder in enabling the world to adapt to climate change and engineers themselves need to be provided with the opportunities to respond to the challenges. For example, engineers have a role in understanding and communicating the limits to engineering adaptation, and also in the implementation of engineering decisions.

In addition, engineers need to be able to make decisions today based on climate change predictions for the future.

## **Understanding and Communicating the Limits to Engineering Adaptation**

The engineering community has an important role to play in assisting policymakers and decision-makers to understand how engineering can help adapt to future climate change. This applies not only to its current potential but also to its future potential.

Irrespective of the level of resilience or adaptability engineered into designs for the future, it is not possible to eliminate all risk from climate change or use engineering design to counteract all the effects of climate change. Therefore, compromises will often be required.

Given the likely controversial nature of such compromises, an early dialogue between the engineering disciplines and policymakers is required to understand the limits to engineering adaptation. The mechanical engineering profession will need to consider how their communications systems can be optimised to increase the effectiveness of the discussions.

An example is the Thames Estuary 2100 project (although this project is for a shorter timescale than being considered here). The project explicitly considers the limits of adaptive engineering for protecting the Thames Estuary against climate change impacts on sea level and storm surge<sup>25</sup>. This study has provided insight into hydraulic performance and possible design considerations of engineering options.

## **The Context for the Implementation of Engineering Decisions**

Whilst engineering may be able to provide some technological solutions to climate change, the implementation of these solutions and their further innovation will depend on political, economic and social will.

For instance, a technological solution for flood defences or natural ventilation could be hampered by non-technological issues. An early dialogue between engineers on their potential to design technological solutions, with those who can create conditions for decision-making based on their research or implementation, may help to develop the capacity of society to respond to the challenges ahead.

## **Enabling Engineers to Make Decisions Today Based on Climate Change Predictions**

Today's engineers are facing projects that will have a lifespan stretching past the year 2100, many of whom may need help to develop the skills needed to deal with climate change and enable their systems to be suitable over their anticipated life spans. The skills needed will depend on the type of the system and other variables.

Understanding the range and type of skills needed by engineers will help to enable justifiable decisions in light of climate change. There is a range of information that is available for decision-makers to use today, and accessing and understanding how to use that information for long-term projects could be an effective next step for the engineering community.

It should also be stated that the engineering ideas presented in this report are by no means fully developed. They are intended to promote discussion and to highlight the fundamental nature of the changes that may be necessary to cope with the climates predicted in the models and the challenges in addressing the issues. The engineering issues also sit within a wider context of global change that is not within the scope of this work.

## **The Duty of Governments**

During this report we have outlined scenarios for the changing of our climate and the effects that it could have on certain important elements of our infrastructure. Engineers are adept at tackling challenges. However, it is necessary that these future challenges are addressed sooner rather than later to allow proper time for research, planning and action.

Engineering of any solution is not an overnight concern. It takes many years, if not decades to create solutions to global problems. The timeline for any new engineering technology to be fully utilised on a global level can well exceed one or two generations (the development of the jet aeroplane and nuclear power are examples of this).

It is therefore advisable that with concerns in areas such as climate change, governments invest significantly more effort in adaptation for the long term, which enables each nation to undertake the necessary steps to ensure its future prosperity and survival.

The Institution of Mechanical Engineers recognises that CO<sub>2</sub> mitigation is vital to our future world and society. However, the effectiveness of past negotiations in leading to reduced emissions is questionable and evidence to date raises doubts that the forthcoming talks in Copenhagen will prove any more successful. It is a duty of government to embrace adaptation and protect the nation against the potential risks of a 'business as usual' outcome.

Understandably for most governments, the idea of actioning projects which will benefit people in future centuries is politically difficult. However, for a nation such as the UK, research and development into adaptation technologies may not only help us cope with future climate impacts and rising sea levels, but also enable us to help more vulnerable nations and provide a highly valuable future component to our economy.

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The iconic 520m Thames Barrier in London is one of the largest moveable flood barriers in the world, protecting 125 square KMs of central London and the 1.25 million people and key infrastructure on which London is dependent. Currently work is being undertaken to extend the life of the Barrier from 2030 to 2100, allowing it to cope with predicted future changes to our climate.



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