# 8 Incorporating climate change within asset management

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A description of established techniques for deriving environmental criteria for the management of assets is presented, followed by a review of the principal issues surrounding the practical application of uncertain knowledge of ~~the~~ future climate. A case study of the Thames Barrier provides an example of best practice.

## 1 Introduction

Physical assets such as buildings, offshore structures and transportation systems operate in a dynamic environment where they are exposed to short, medium and long-term variability in ambient environmental conditions. An important input to asset management is an adequate understanding of this variability. This typically includes the estimation of environmental conditions that can be expected over the life of an asset (e.g. an offshore structure) or a system of assets (e.g. a transportation system). Engineers and asset managers employ these environmental criteria as the basis for understanding the impact of the environment on proposed or existing ~~physical~~ assets. Criteria may be derived on an asset-specific basis or through the application of predetermined codes. Environmental criteria are used as inputs to the design and construction of an asset, to the planning of operations and to gain an understanding of through-life maintenance requirements.

Environmental criteria usually take the form of a statistical view of the variability of conditions within which the asset must operate: for example, wind speed variability to determine the wind loading on a building, wave height variability to determine the loading on an offshore structure, or air temperature variability as an input to the design of railways or roads.

For operational planning, daily, weekly, monthly or seasonal variability of an environmental parameter which has an impact is often required: for example, the likely exceedance of a threshold limiting condition for the operation of a port or airport. To understand through-life maintenance costs, an understanding of the relationship

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between environmental factors and the deterioration of the asset is needed, such as the impact of continuous wave loading on the deterioration of key structural components of an offshore structure.

A critical input to design is an analysis of the most extreme environmental conditions that an asset must be designed to withstand: for example, the maximum wind speed that a building must withstand or the extremes of air temperature under which a road or railway must be able to operate. Design codes and asset-specific design studies typically provide an estimation of the magnitude of the most extreme event that might be expected to occur at least once in a specified return period. The selection of return periods is based on the expected life of the asset and the economic, safety and environmental risks associated with damage or structural failure. The selection of different return periods permits trade-offs between economic, safety and environmental impacts and the costs of construction to be taken into account. For example, offshore oil and gas production facilities have typically been designed for a 100 year return period, and coastal nuclear power stations for a return period of 10 000 years or more. Steven Male talks more about the importance of climate change in long-life asset management in Chapter 3, 'The challenges facing public sector asset management'.

## 2 Use of time histories

The fundamental basis for meeting the environmental information needs of asset management is the analysis of time histories of environmental variables. Time histories can be derived in a number of ways. They may be calculated (e.g. astronomical tidal elevation) or measured directly (e.g. location-specific measurements of wind speed and direction). Empirical formulae are frequently employed to compute the value of a variable at a location which differs from where it was observed; for example, wind speeds measured at one elevation are often converted to values at a different elevation based on empirical factors derived from experiment. For spatial interpolation, numerical modelling techniques are frequently employed. Numerical modelling also provides a basis for deriving time histories of one variable from knowledge of another; for example, ocean wave characteristics derived from surface winds based on the knowledge of the physics of wave generation. Many different types of model are widely used to describe data and processes.

For determining extremes, the length of available time histories is almost always significantly less than the design return period, so probabilistic techniques are used to extrapolate to longer periods.

Generalised extreme value distributions such as Weibull, Fisher Tippett and Gumbel (Kotz and Nadarajah, 2000) or generalised Pareto distributions (Falk *et al.*, 2004) are used for this purpose.

## 3 Uncertainty in environmental criteria

Sources of time history data and the tools used to analyse or extrapolate them are subject to a range of generic uncertainties.

For measured data there are uncertainties associated with the accuracy and precision of measurement devices. Empirical factors for inferring variation in an environmental parameter at a location different to where it was measured are generalised approximations. Numerical models introduce uncertainty through inadequate mathematical representation of processes, errors in parameterisation, omission of important processes, and spatial and temporal smoothing across model grids and time steps.

In Chapter 5, 'Asset management strategy: leadership and decision-making', Penny Burns highlights the risk of basing future strategy on historical information alone. A key source of uncertainty is the assumption that past time histories will be statistically representative of the future. Time histories must be long enough to capture annual variability, but how long do they need to be to adequately capture inter-annual variability?

It has long been understood that the natural climate is not stationary. This is self-evidently the case over geological timescales, where we know that climatic conditions, such as temperature, precipitation and sea level, lay well outside of anything observed during human history. Even over the period of human history, climate is known to have varied considerably. As climate science has advanced, natural climate cycles have been identified which operate on multi-year scales.

The best known of these is the El Niño-Southern Oscillation (ENSO). Driven by large-scale sea surface temperature fluctuations in the tropical Eastern Pacific, this natural climate cycle is associated with floods, droughts and other disturbances at a range of locations around the world. ENSO is the most prominent known driver of inter-annual variability in weather and climate around the world, and has a period of between 3 and 8 years (Glantz, 2000).

A number of other long-period natural cycles which have far-reaching effects have also been identified. Examples include the North Atlantic Oscillation (NAO), which is responsible for much of the variability of weather in the North Atlantic region during the November to April period, affecting wind speed and wind direction, temperature and

moisture distribution and the intensity, number and track of storms (Hurrell and Loon, 1997), and the Indian Ocean Dipole (IOD), which influences climate throughout the Indian Ocean region, including effects on the magnitude of Indian monsoons (Saji *et al.*, 1999).

Established techniques for deriving environmental criteria are all based on the assumption that the use of a long enough time history of past variability will capture inter-annual variability sufficiently to ensure that it is incorporated into statistical summaries and projections of extreme events.

This implicit assumption of stationarity is no longer valid when there is a cycle longer than the length of the time history or if a single event from a class of events, which are absent in the observed or modelled past, occurs; for example, the occurrence of a hurricane at a location where no hurricanes have previously been observed. A cycle or type of event not captured in the time history will mean that the statistics of the past will not be representative of the future. Most significantly in the context of climate change, non-linear long-term trends which may extend far into the future are explicitly excluded.

## 4 Climate change

There is now a high level of confidence that our climate is changing due to human activity and especially due to emissions of greenhouse gases.

The 'greenhouse effect' is an essential component of maintaining a habitable planet. Naturally occurring greenhouse gases (especially carbon dioxide, methane and nitrous oxide) effectively trap part of the heat radiated from the earth's surface. Were these natural greenhouse gases absent, the earth would be too cold to support life as we know it.

Direct measurements of carbon dioxide in the atmosphere show that its concentration has been progressively increasing over the last 50 years. Indirect measurements based on analysis of gas bubbles trapped in ice cores show a carbon dioxide increase of approximately one-third since the start of the industrial revolution. The majority of the increase from a pre-industrial level of 280 parts per million to a level of 387 parts per million in 2009 has been firmly attributed by the Intergovernmental Panel on Climate Change (IPCC) to the burning of fossil fuels and changes in land use (IPCC, 2007a). Current atmospheric concentrations of carbon dioxide far exceed the natural range of the last 650 000 years (IPCC, 2007a).

The effects of increased greenhouse gases and land use changes on global climate are determined by the analysis of a wide variety of

observations and measurements and the use of mathematical models which aim to provide insight into future change. The most sophisticated of these are the so called atmosphere–ocean general circulation models (AOGCMs), which aim to reproduce many of the processes through which greenhouse gases influence the earth's climate.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007a) provides a synthesis of observed and projected results of anthropogenic climate change. In summary:

- The IPCC report finds with a very high confidence that the globally averaged net effect of human activities since 1750 has been one of warming. Global mean temperatures have been rising over the last century with a more rapid rise since 1970. Average global lower atmosphere temperatures have increased by 0.74°C, with most of this increase having occurred in the last 50 years. Climate models used to estimate temperature changes all project that it will be warmer in the future, with global average warming of about 0.4°C expected during the next 20 years. Over the longer term, these models project average global temperature increases ranging from 1.1°C to 6.4°C by the end of the 21st century with considerable regional variation. Extreme temperatures are also expected to increase. These projections are the result of integrating the results from a range of global climate models under a variety of scenarios for future economic activity and energy use. Over the last 50 years, the frequency of cold days and nights has declined and the frequency of hot days, hot nights and heat waves has increased. The number of days with temperatures above 32°C and 38°C has been increasing since 1970, as has the intensity and length of periods of drought. The report finds it virtually certain that warmer and more frequent hot days and nights will occur over most land areas during the next century.
- Over the past century, precipitation has increased in several regions while drying has been observed in others, notably in Africa and Asia. During the 21st century, increases in the amount of precipitation are very likely in high latitudes while decreases are likely in most subtropical land regions. While the average levels of precipitation will vary by region, the incidence of extreme precipitation events is expected to increase.
- The IPCC reports that the globally averaged rise in sea level during the 20th century was 0.17 m and that average sea level rose at a rate of 1.8 mm per year between 1961 and 2003, with the majority of this rise being due to the thermal expansion of seawater. Excluding

the effects of rapid changes in ice flow from the polar ice sheets, model-based projections for global sea level rise over the next century across multiple socio-economic scenarios are in the range 0.18–0.59 m. These estimates are being re-examined in the light of new evidence that glaciers and ice sheets could experience more rapid melting, leading to a significantly larger global mean sea level rise by the end of the century (Pfeffer *et al.*, 2008).
- It is likely that future tropical cyclones will become more intense, with higher peak wind speeds and heavier precipitation. There is currently insufficient evidence to clearly identify trends for other storm phenomena.

## 5 Uncertainty in climate observations and projections

Observations of climate change are subject to a range of measurement and analysis uncertainties. It remains the case that the earth is sparsely monitored, and this is especially true for the oceans. The inadequacy of the observational base, measurement accuracy and analytical techniques all contribute to uncertainty in global and regional measures of observed climate change.

The cascade of uncertainty surrounding projecting future climate begins with forcing uncertainties; to predict future anthropogenic climate change requires knowledge of future greenhouse gas emissions and land use changes. Even if there were perfect techniques for projecting the impact of a given level of greenhouse gas accumulation in the atmosphere, we cannot reliably predict what future emissions will be or how patterns of future land use will change. All that can be done is to work with realistic scenarios of future global socio-economic development and the possible emissions pathways that they might create. It will be possible to narrow the uncertainly in future emissions scenarios as national and international policies on mitigating greenhouse gas emissions are developed and implemented.

The IPCC uses a range of scenarios (Nakicenovic and Swart, 2000) derived from the IPCC Special Report on Emissions Scenarios (SRES):

- The A1 scenario family describes a future world of very rapid economic growth, a global population that peaks mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. A major underlying theme is convergence among regions of the globe, with a substantial reduction over time in regional differences in per capita income. The A1 family is split into three groups that describe alternative directions

of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B).

- The B1 scenario family describes a convergent world with the same population trajectory as in the A1 storyline, but with rapid changes towards a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies.
- The A2 scenario family describes a very heterogeneous world, with the underlying theme of self-reliance and preservation of local identities. The global population increases continuously, economic development is regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in the other storylines.
- The B2 scenario family describes a world that emphasises local solutions to economic, social and environmental sustainability (i.e. a heterogeneous world as in A2). The global population increases continuously at a rate slower than A2, with intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines.

It is telling that emissions are currently tracking above the most intense fossil fuel scenario established by the IPCC SRES (Global Carbon Project, 2008).

A further area of forcing uncertainty concerns understanding how emissions of greenhouse gases translate into actual concentrations in the atmosphere and are therefore 'available' to affect the earth's radiative balance. Natural land and ocean carbon dioxide sinks largely control this, and are currently responsible for removing just over 50% of human greenhouse gas emissions over the 2000–2007 period. There is evidence that the efficiency of these natural sinks is decreasing (Global Carbon Project, 2008). Reliably predicting future efficiency changes is not yet possible since the bio-geochemical processes involved are highly complex and poorly understood.

Modelling of the global and regional climate response to greenhouse gases is also subject to major uncertainties. The often-cited multi-model graph of global surface warming (IPCC, 2007a) illustrates this uncertainty for a range of emissions scenarios.

It is clear from Fig. 8.1 that the likely range around the best estimate for the last decade of the 21st century is large. It must also be understood that this range is not a measure of total uncertainty, since not all processes that determine future climate are represented in the models.

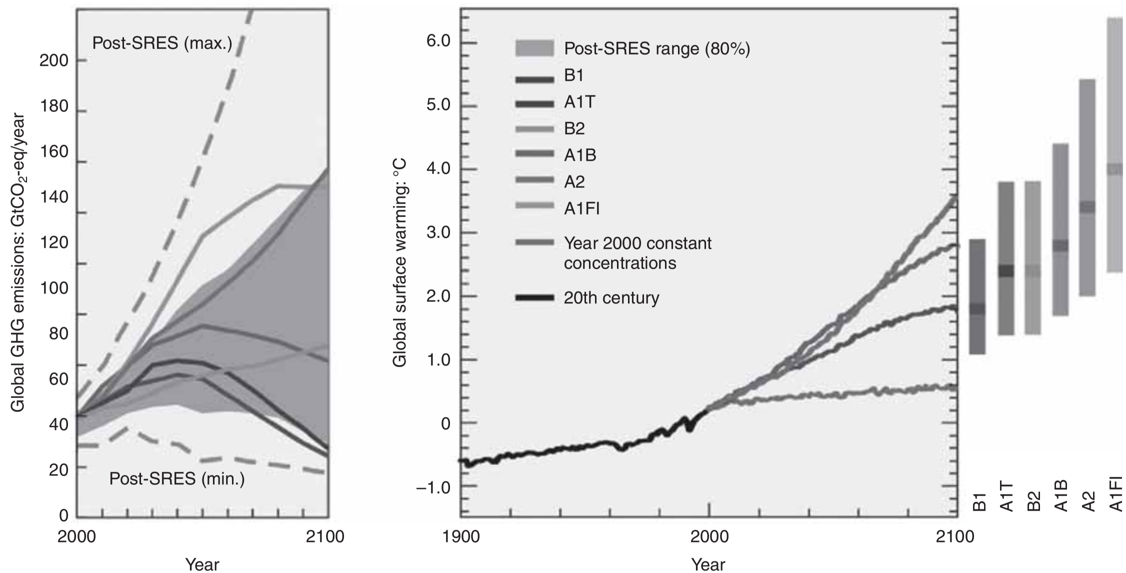


**Fig. 8.1** *Left panel*: Global GHG emissions (in $GtCO_2$-eq) in the absence of climate policies: six illustrative SRES marker scenarios and the 80th percentile range of recent scenarios published since SRES (post-SRES) (gray shaded area). Dashed lines show the full range of post-SRES scenarios. The emissions include $CO_2$, $CH_4$, $N_2O$ and F-gases. *Right panel*: Solid lines are multi-model global averages of surface warming for scenarios A2 A1B and B1, shown as continuations of the 20th-century simulations. These projections also take into account emissions of short-lived GHGs and aerosols. The lowest line is not a scenario, but is for Atmosphere-Ocean General Circulation Model (AOGCM) simulations where atmospheric concentrations are held constant at year 2000 values. The bars at the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090–2099. All temperatures are relative to the period 1980–1999. (From IPCC (2007a).)

Understanding the effects of anthropogenic climate change on the characteristics of natural cycles such as ENSO and the NAO is also currently beyond the capability of climate models.

Problems with determining uncertainty become more acute in moving from a global to regional scale and from modelling temperature to modelling more complex effects such as changes in precipitation. At regional scales, AOGCMs produce not only different quantities of change in precipitation but also changes in different directions (Jenkins and Lowe, 2003).

Global and regional models produce climate change scenarios that are too coarse in both space and time for determining site-specific impacts. One possible means of addressing this is to downscale to finer spatial and temporal resolution using statistical or dynamical modelling. An example is the UK Climate Projections (UKCIP) (Murphy *et al.*, 2009), which makes extensive use of downscaling techniques to derive fine resolution outputs (25 km × 25 km UK land grid squares). The UKCP also include statistical representation of future daily climate from 2020 onwards on an even finer scale (5 km × 5 km grid squares) generated on the basis that future climate will be consistent with the statistics of the current climate. By adding further modelling and statistical procedures, downscaling adds much additional uncertainty to already uncertain global and regional model projections. As a result, such downscaled products must be used with considerable caution.

The final source of uncertainty concerns so-called tipping points, or in IPCC terms, large-scale singularities (IPCC, 2007a). These are extreme, sometimes irreversible, changes in the earth system such as an abrupt cessation of the North Atlantic Meridional Overturning Circulation, rapid global sea level rise due to Antarctic or Greenland ice sheet melting, or abrupt releases of methane from permafrost regions or the deep ocean. Such events are at the extremes of probability and cannot be reliably predicted. Although thought to be extremely improbable, their impact is potentially very large. John Woodhouse explains how these uncertainties need to be taken into account when developing strategic asset management plans in Chapter 2, 'Asset management in the oil and gas, process and manufacturing sectors'.

## 6 Adapting to climate change

It is clear that knowledge of the past is no longer a valid basis for making projections about the future. Since the effects of long-term

anthropogenic changes in climate are not incorporated into established techniques for generating environmental criteria and since the magnitude of the possible changes are significant over the design live of many assets, then some means of including such changes in asset management decision-making must be developed.

There is an obvious problem here. Although our knowledge of the past (and present) environment is subject to the errors already described (measurement errors, analytical errors, interpolation errors), these errors are generally small and are quantifiable. Experience has tuned the estimation of environmental criteria and their use in asset management such that risks associated with uncertainty are generally accommodated though appropriate safety margins. By contrast, uncertainties in the projection of future anthropogenic climate change are known to be large, include unknowable uncertainties associated with knowledge of future emissions, and are determined based on models which poorly represent or omit important processes. Past experience in ensuring adequate safety margins is of limited value in this non-stationary and uncertain climate future.

If future climate were predictable with much greater certainty, then the largely deterministic methods currently used to provide environmental criteria for engineering design and asset management decisions could be readily adapted to incorporate known long-term trends not captured in historical data. However, given the uncertainties concerning the magnitude and timing of climate factors, it is clear that these methods can no longer adequately address the range of environmental conditions that engineers and asset managers now need to consider.

Incorporation of climate change into asset design has so far been limited, with the vast majority of new infrastructure continuing to be designed against established codes or historical time history-based asset-specific environmental criteria. Management of the majority of existing assets also continues to be on the basis of established techniques for the estimation of environmental criteria.

In some cases, the results of the analysis of historical time histories and probabilistic extreme value analysis have been corrected for measured long-term trends (for example, extrapolation of present rates of sea level rise over the design life of a coastal facility). In others, a more precautionary approach has been employed with application of safety factors based on a combination of model projections and expert opinion.

Where climate change has been considered in more detail, an iterative risk assessment approach is beginning to find wider application.

## 7 Climate risk assessment

A risk assessment approach takes account of four major conceptual factors in assessing climate change impact and adaptation: exposure to climate stressors; vulnerability; resilience; and adaptation. These concepts and their definitions are borrowed from ecological and hazard assessment practices.

Climate change exposure is 'the nature and degree to which a system is exposed to significant climate variations' (IPCC, 2001). Exposure is a combination of the probable range of a climate stressor and the physical characteristics of a geographical location, e.g. height above sea level for a coastal facility. Exposure represents the likelihood that the climate stress will affect a particular asset or asset system.

Vulnerability refers to the potential for loss due to exposure to a particular climate stressor (Tobin and Montz, 1997). The IPCC defines vulnerability as 'the degree to which a system is susceptible, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude and rate of climate change to which a system is exposed, its sensitivity, and its adaptive capacity' (IPCC, 2007b). Vulnerability considers the structural strength, integrity and function of assets or asset systems in terms of the potential for damage or functional disruption as a result of climate stressors. Risk to an asset is a function of exposure and vulnerability.

Resilience is used to refer to the capacity of a system to absorb disturbance without losing essential function. In the context of physical assets or asset systems, it is the ability of a system to continue to operate as a result of built-in redundancy, e.g. a transportation system's ability to continue to operate despite loss of a single road or bridge or the relative ease with which a single asset can be repaired or replaced. The context for resilience is a combination of physical constraints on repair or replacement, socio-economic limitations (public support, economic and social resources) and system redundancy.

Adaptation is the 'adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities' (IPCC, 2007b). An associated concept, 'adaptive capacity', refers to 'the ability of a system to adjust to climate change, including climate variability and extremes, to moderate potential damages, to take advantage of opportunities, or to cope with consequences' (IPCC, 2007b).

Adaptive strategies fall into three categories: protect, accommodate and retreat. These adaptive strategies are derived from the IPCC

framework for assessing coastal adaptation options (Bijlsma *et al.*, 1996). Within the context of a coastal region, a protection strategy might aim to protect assets from flooding by constructing hard or soft structures, e.g. sea walls, beach nourishment or wetland restoration. Accommodation may call for preparing for periodic flooding by having operational plans in place. Retreat involves no attempt to protect the asset, e.g. a facility or structure may be abandoned under certain conditions. Although applied specifically to coastal examples, these adaptive strategies may be generalised to all types of asset and asset geographical locations.

An important concept in the risk assessment approach is that of thresholds. Thresholds are defined as points at which stimuli lead to specific responses (Parry and Carter, 1998; Jones, 2001). In the context of asset management, these are points within an assessment or decision-making process at which specific actions are taken. Thresholds can be quantitative indicators such as observed extremes (e.g. sea levels observed to exceed a particular level), may be condition driven (e.g. when the condition of an infrastructure component falls below a certain standard) or may be economic (e.g. when replacement costs less than repair).

## 8 Use of risk assessment approaches

A number of authors have outlined the principles of application of a risk-based approach to climate change-related decision-making (e.g. Willows and Connell, 2003; Sussman and Freed, 2008).

The US Climate Change Science Program (CCSP) provides a comprehensive evaluation of a risk-based approach to the evaluation of climate change risks to transportation systems and infrastructure on the Gulf Coast (CCSP, 2008).

Among the limited number of asset-specific studies that have employed a risk analysis and impact assessment framework, a number of different approaches have been taken.

In the UK, Associated British Ports made use of a risk assessment that relied on expert opinion to judge risk levels for UK ports (ABP Marine Environmental Research, 2004). For this study, risks were broken down into four categories: flooding, insurance, physical damage and disruption. Port managers and other experts were then asked to classify risk for each impact as very low risk, low risk, moderate risk, high risk or very high risk.

For the UK rail network, Eddowess *et al.* (2003) developed a framework for prioritising risks that integrates the probability that a particular

climate effect would impact the rail industry – risk likelihood – with the scale of the impact if it did occur – risk impact. Risk likelihood combines an assessment of the present-day vulnerability to specific climate factors with projections of how they might change under climate change scenarios. Risk impact takes into account the severity of a given impact, the amount of infrastructure affected and the ability to adapt to the change.

Transit New Zealand developed a methodology for determining thresholds for taking action by using a two-stage process (Kinsella and McGuire, 2005). The first stage constituted a decision tree that examined the necessity of taking action in the near term. No action was deemed necessary if it was determined that a given impact was unlikely to occur before 2030, the impact would not occur within the design life of the facility (for facilities with lifetimes less than 25 years) or if current standards would adequately address climate impact. If present-day action was deemed necessary, the second-stage analysis determined the feasibility of taking action by comparing the costs of doing nothing, retrofitting the infrastructure or designing new infrastructure.

The Asian Development Bank outlines a number of case studies of a risk-based approach to asset design and management in developing countries (ADB, 2005). These include the design of a road and a breakwater, 'climate proofing' of a coastal town and the consideration of climate risks within two national development plans.

## 9 A case study: the Thames Estuary 2100 Project

Currently, the most exhaustive UK application of a risk analysis approach is that undertaken by the Environment Agency for Thames flood protection. The Thames Estuary 2100 Project (TE2100) has developed a strategic plan for managing flood risk on the Thames Estuary over the next 100 years. This ~~case study~~ describes the way in which the plan takes account of the uncertainties of future climate change. The approach to option development and adaptation was developed by David Ramsbottom (HR Wallingford Limited) and Tim Reeder (UK Environment Agency), who contributed this case study.

### *9.1 Options for flood risk management*

Options have been developed for managing flood risk over the next 100 years. Each option consists of a sequence of interventions. Each intervention is triggered when a threshold is reached, for example the

design water level at a particular location on the estuary. Interventions consists of a 'portfolio (or set) of responses', where a response is a particular measure, for example a new barrier. A portfolio of responses might consist of defence raising, improvements to the Thames Barrier, and some new flood control structures.

The first step in developing the options was to identify portfolios of responses that could manage future increases in surge tide level and fluvial flows. The portfolios were hydraulically modelled to determine how much increase in flood water level they could accommodate. Portfolios for tidal flooding were plotted against the maximum surge tide water level at Southend (just outside the mouth of the estuary) that can be accommodated by the portfolio. A series of portfolios, each of which can accommodate a different increase in surge tide level, can then be linked to form a complete option for managing flood risk.

Options were designed for an increase in surge tide level of over 4 m. This required an assessment of the ease with which one portfolio can be adapted to another portfolio that provides a higher level of protection against flooding. Four generic options were developed using this procedure. These generic options represent the following conceptual approaches:

- Option 1 – improve the existing flood defence system including the Thames Barrier.
- Option 2 – maximise tidal flood storage in the floodplains.
- Option 3 – new barrier.
- Option 4 – new barrage (or barrier with locks).

Figure 8.2 shows how portfolios have been combined and simplified to develop the four generic options. The options are plotted against rise in the surge tide level. By adding the amounts of sea level rise expected for different climate change scenarios in 2100, options that can manage flood risk over the next 100 years under different future scenarios of sea level rise are identified. The figure shows that all four generic approaches are suitable for a sea level rise in 2100 of about 1 m, which corresponds to current UK government guidance (Defra, 2006). However, for the most extreme scenario, only option 4 is suitable.

Climate change studies undertaken as part of the TE2100 project have revised the extreme scenario of a 4 m increase in sea level downwards to an increase of 2.7 m by 2100.

The final options in the TE2100 plan are based on the generic options described above. Each generic option includes several suboptions, for example, generic option 3 has a number of different locations for barriers. The options are designed for current government guidance on climate change but are adaptable for faster (or slower) rates of change.

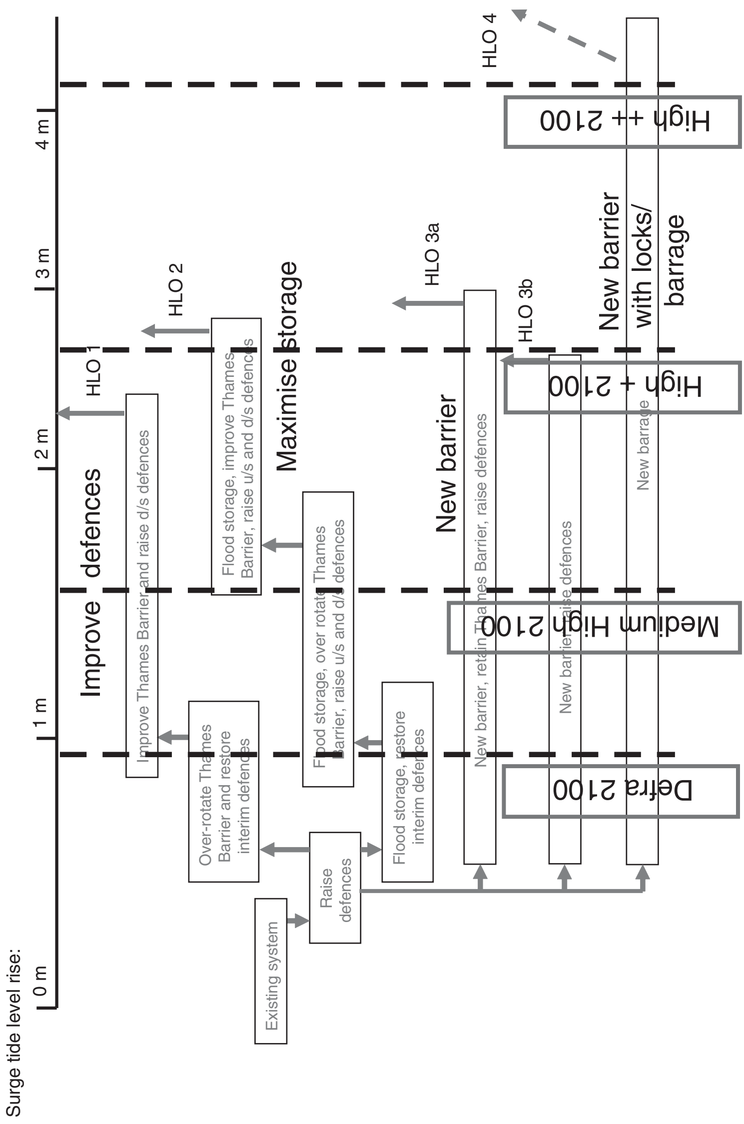


**Fig. 8.2** Generic options for managing sea level rise

## 9.2 Adaptation for future change

The preferred estuary-wide flood risk management option takes account of future changes, including climate change, physical changes to the estuary, and deterioration of the existing flood risk management system. Whilst the options have been designed for particular assumptions about future change, the magnitude of future changes is essentially unknown. Rates of change may be faster or slower than the rates assumed, and therefore the dates when interventions are required will change.

An approach to adaptation has been developed which takes account of uncertainty in future change, and enables decisions to be made that are based on actual rates of change.

The main future changes that will affect the implementation of the adaptation plan are:

- Climate change. This presents the greatest challenge in terms of future uncertainty. The impacts include expected rises in mean sea level, peak surge tide level, wave heights and fluvial flows.
- Socio-economic change.
- Deterioration of the existing flood defence assets.
- The physical environment, including estuary morphology.
- Public attitudes to flood risk.

The types of adaptation envisaged within the plan to cope with the uncertainty of future change include the following:

- Changes to the timing of new interventions.
- Ability to change between options.
- Adaptation of engineering responses.
- Land use planning that provides flexibility in the selection of options.
- Adaptation to new infrastructure, for example a new estuary crossing.

The approach to adaptation is as follows:

- Indicators that represent the main drivers of flood risk management are identified.
- For each indicator, the thresholds where responses are needed to maintain the required level of flood protection are identified. For example, in the case of climate change, this includes a particular sea level at the Thames Barrier.
- The lead time for implementing each portfolio of responses is estimated. This is the time needed to plan and construct the

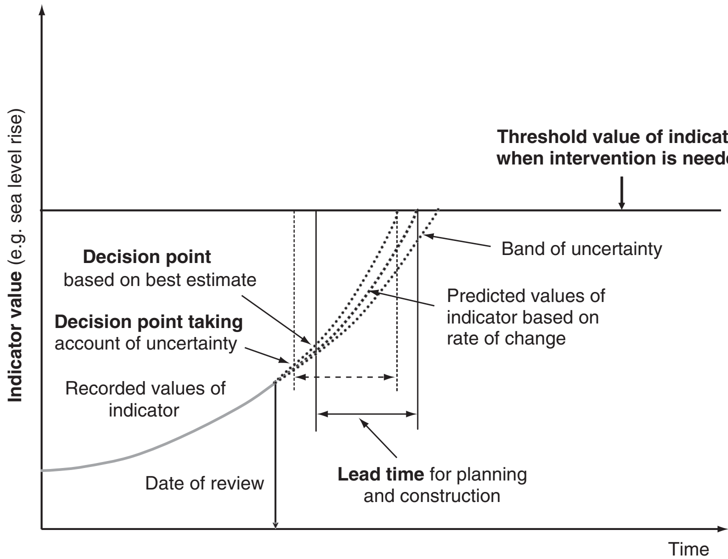


**Fig. 8.3** Relationship between a threshold, lead time and decision points

portfolio of responses before it is actually needed. A decision point is the date by which the decision to implement the portfolio of responses must be taken. Figure 8.3 illustrates the concept of lead times and decision points.

The timing of a decision to implement an intervention is based on:

- The rate of change of the indicator (which is unlikely to be linear).
- The threshold value when an intervention is required.
- An estimate of how the indicator will continue to change, in order to estimate the date when it reaches the threshold value.
- The lead time for planning and constructing the intervention.

The plan includes assumed dates when the responses will be required, and therefore assumed dates when decisions must be made. The indicators are monitored, and the monitoring results are used to update the estimated dates when portfolios of responses must be implemented, and to revise, the dates when decisions must be made.

If the actual values of the indicators do not correspond with the assumed values, the preferred option will be affected. This can affect the timing and choice of interventions. The plan is updated using the revised estimates of the dates when thresholds will be reached and decisions must be taken.

If significant changes occur in the expected dates when thresholds will be reached, the choice of the preferred option should be reviewed. This is because an alternative option may be more effective for managing flood risk under the changed circumstances. Alternative options are included in the plan, although it would be wise to consider whether there are any others available when the options are reviewed. For example, new infrastructure projects may provide opportunities to combine new structures such as estuary crossings with flood risk management.

The procedure outlined above will take place over a number of years. The preferred option and the alternatives all involve a similar approach until a critical water level threshold is reached at the Thames Barrier. The critical drivers for this are the mean sea level and peak surge tide level. The current assumed date for major interventions is 2070, based on present UK government guidance on climate change.

The plan includes responses that should be implemented within the next few years, including improvements to defences and habitat creation. It is, therefore, necessary to establish the monitoring network as soon as practicable to facilitate decision-making for these cases. This will be helped by the fact that several key indicators are already monitored.

## 10 Conclusions

Scientific evidence that human activity is resulting in climate change is near unequivocal. That changes in climate are now a significant factor in the design and management of assets is without question. However, political consensus regarding climate change mitigation is far from certain, and scientific capacity to project the trajectory of local climate for a given mitigation framework is very limited.

Faced with these large political and scientific uncertainties, engineers and asset managers must make effective use of a limited capacity to accurately project environmental conditions over the lifetime of assets and asset systems. Gone is the ability to look in the rear-view mirror at the past in order to adequately understand the future.

Engineers and asset managers are used to working in a framework where they are provided with reliable statistics about the future environment. If adaptation to climate change is to be effective they must now learn to work with much more uncertain information about a future climate that will be significantly different to that of the past.

## References

ABP Marine Environmental Research 2004. *Climate Change 2003 Port Template: Findings from the First Assessment*. Report Number R.1061. Associated British Ports, London.

ADB 2005. *Climate Proofing: A Risk Based Approach to Adaptation*. Asian Development Bank Pacific Studies Series. Asian Development Bank, Manila.

Bijlsma, L., Ehler, C. N., Klein, R. J. T. *et al*. 1996. Coastal zones and small islands. In: *Climate Change 1995: Impacts, Adaptations, and Mitigation of Climate Change: Scientific-Technical Analysis. Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, pp. 289–324.

CCSP 2008. *Impacts of Climate Change and Variability on Transportation Systems and Infrastructure: Gulf Coast Study, Phase I*. A Report by the US Climate Change Science Program and the Subcommittee on Global Change Research (Savonis, M. J., Burkett, V. R. and Potter, J. R., eds). Department of Transportation, Washington, DC.

Defra 2006. *Appraisal of Flood and Coastal Erosion Risk Management: A Defra Policy Statement*. Department for Environment, Food and Rural Affairs, London.

Eddowess, M. J., Waller, D., Taylor, P. *et al*. 2003. *Rail Safety Implications of Weather, Climate and Climate Change: Final Report*. Rail Safety and Standards Board, London.

Falk, M., Hüsler, J. and Reiss, R. D. 2004. *Laws of Small Numbers: Extremes and Rare Events*, 2nd edn. Birkhäuser, Basel.

Glantz, M. H. 2000. *Currents of Change: Impacts of El Niño on Climate and Society*, 2nd edn. Cambridge University Press, Cambridge.

Global Carbon Project 2008. *Carbon Budget and Trends 2007*. www.globalcarbonproject.org.

Hurrell, J. W. and Loon, H. V. 1997. Decadal variations in climate associated with the North Atlantic Oscillation. *Climatic Change*, 36: 301–326.

IPCC 2001. *Climate Change 2001: Impacts, Adaptations, and Vulnerability*. IPCC. Cambridge Press, New York.

IPCC 2007a. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

IPCC, 2007b. *Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Jenkins, G. J. and Lowe J. 2003. *Handling Uncertainties in the UKCIP02 Scenarios of Climate Change*. Hadley Centre Technical Note 44. Met Office Hadley Centre, Exeter.

Jones, R. N. 2001. An environmental risk assessment/management framework for climate change impact assessment. *Natural Hazards*, 23: 197–230.

Kinsella, Y. and McGuire, F. 2005. *Climate Change Uncertainty and the State Highway Network: A Moving Target*. Transit New Zealand, Auckland.

Kotz, S. and Nadarajah, S. 2000. *Extreme Value Distributions: Theory and Applications*. Imperial College Press, London.

Murphy, J. M., Sexton, D. M. H., Jenkins, G. J. *et al*. 2009. *UK Climate Change Projections Science Report: Climate Change Projections*. Met Office Hadley Centre, Exeter.

Nakicenovic, N. and Swart, R. (eds) 2000. *Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge.

Parry, M. and Carter, T. 1998. *Climate Impact and Adaptation Assessment: Guide to the IPCC Approach*. Earthscan, London.

Pfeffer, W. T., Harper, J. T. and O'Neel, S. 2008. Kinematic constraints on glacier contributions to 21st century sea-level rise. *Science*, 321: 1340–1343.

Saji, N. H., Goswami, B. N., Vinayachandran, P. N. and Yamagata, T. 1999. A dipole mode in the tropical Indian Ocean. *Nature*, 401: 360–363.

Sussman, F. G. and Freed, J. R. 2008. *Adapting to Climate Change: A Business Approach*. Pew Center on Global Climate Change, Washington, DC.

Tobin, G. A. and Montz, B. E. 1997. *Natural Hazards: Explanation and Integration*. Guilford Press, New York.

Willows, R. I. and Connell, R. K. (eds) 2003. *Climate Adaptation: Risk, Uncertainty and Decision-making*. UKCIP Technical Report. UKCIP, Oxford.