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Phil. Trans. R. Soc. A 2011 **369**, 196-216

doi: 10.1098/rsta.2010.0277

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Rethinking adaptation for a 4°C world

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With weakening prospects of prompt mitigation, it is increasingly likely that the world will experience 4°C and more of global warming. In such a world, adaptation decisions that have long lead times or that have implications playing out over many decades become more uncertain and complex. Adapting to global warming of 4°C cannot be seen as a mere extrapolation of adaptation to 2°C; it will be a more substantial, continuous and transformative process. However, a variety of psychological, social and institutional barriers to adaptation are exacerbated by uncertainty and long timeframes, with the danger of immobilizing decision-makers. In this paper, we show how complexity and uncertainty can be reduced by a systematic approach to categorizing the interactions between decision lifetime, the type of uncertainty in the relevant drivers of change and the nature of adaptation response options. We synthesize a number of issues previously raised in the literature to link the categories of interactions to a variety of risk-management strategies and tactics. Such application could help to break down some barriers to adaptation and both simplify and better target adaptation decision-making. The approach needs to be tested and adopted rapidly.

Keywords: adaptation; uncertainty; decision-making; risk management;
complexity; climate change

1. Introduction

The 4° and Beyond conference in Oxford (2009) presented pressing evidence that more global warming may occur much sooner than previously thought likely [1]. The 15th Conference of the Parties meeting in Copenhagen that occurred shortly afterwards provided little encouragement that these large changes can be prevented through politically negotiated emissions reductions [2]. Potential impacts associated with an increase of more than 4°C in global average temperatures are severe, particularly as even higher levels of change may be experienced locally (e.g. [3–5]). There is no doubt, therefore, that the subject

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One contribution of 13 to a Theme Issue ‘Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications’.

of adaptation in a '4°C world' (here, we use this shorthand to refer to the world with a serious prospect of average global warming of 4°C or more) will become an increasingly urgent concern.

A stronger prospect of more climate change occurring sooner places a greater priority on considering substantial and continuing adaptation activities, and in particular on considering adaptation decisions with long *lifetimes*. Here, we define *decision lifetime* as the sum of *lead time* (the time from first consideration to execution) and *consequence time* (the time period over which the consequences of the decision emerge). Although a variety of issues regarding these decisions have been raised in the academic literature, these have not been absorbed by practitioners. Pittock & Jones ([6], pp. 9 and 15) made the critical point that 'Climate change in the foreseeable future will not be some new stable 'equilibrium' climate, but rather an ongoing 'transient' process', requiring 'an on-going adaptation process'. However, we explore some psychological and institutional barriers to acting on adaptation, showing that many of these are exacerbated for the more difficult, transformational and long-lifetime decisions.

The core purpose of this paper is to advance understanding of these adaptation decisions with a long lifetime, and to contrast them with other, simpler, adaptation decisions. We present an initial classification of decision types that is aimed at helping decision-makers to arrive at better adaptation solutions. The perspective of this paper reflects the experience of the authors working with practitioners: we write with the developed world in mind, based on our experience in planned adaptation occurring in Australia and the UK. The classification of decisions is universal, but we recognize that the context of adaptation decisions in developing countries may often differ.

Two recent papers provide a springboard for our analysis. Adger & Barnett [7] voice four concerns about adaptation to climate change, which we paraphrase as: the task is unexpectedly urgent and hard; adaptive capacity will not necessarily translate into action; there is widespread existing maladaptation; and the measurement of adaptation success is profoundly complex. Hallegatte [8] makes the same first point, which indeed underlies this entire Theme Issue: the speed and the magnitude of potential change creates major adaptation challenges, as does the ongoing nature of uncertainty about the future, a point which we elaborate further below. He goes on to emphasize the need for decision-makers today to adjust their practices and decision-making frameworks to account for these realities, and proposes five approaches to reducing the riskiness of their management in the face of uncertainty. These are '(i) selecting 'no-regret' strategies that yield benefits even in absence of climate change; (ii) favouring reversible and flexible options; (iii) buying 'safety margins' in new investments; (iv) promoting soft adaptation strategies, including (a) long-term (perspective); and (v) reducing decision time horizons' ([8], p. 240).

We concur with Hallegatte [8] that, while it is a challenge to include climate change in decision-making frameworks, there are many existing tools that may be used. However, his five approaches need to be framed within a broader classification of decision types. In §2, we consider how adaptation is currently viewed, identifying issues that are not yet embedded in practitioner thinking, but which are important in facing the challenges of a 4°C world. In §3, we explore some key barriers to acting on adaptation, noting how these particularly affect decisions with longer term implications. Section 4 then sets out an initial classification of

the different types of adaptation decisions and responses which may be needed in a 4°C world, and presents some examples. We conclude by considering how this approach might be further developed.

2. Uncertainty and current issues in adaptation

Both Hallegatte [8] and Adger & Barnett [7] emphasize uncertainty about the future arising from climate change. In a broad sense this arises both from the *social uncertainty* about whether and when mitigation efforts will be agreed and achieved, as well as from the *scientific uncertainty* about how the many feedbacks in the Earth system operate, arising from imperfect climate modelling, the role of tipping points [9] and other limits to our understanding of the system. Hallegatte [8] notes that these sources of uncertainty will not go away in the foreseeable future: social uncertainties will play out over decades, and recent experiences of improving scientific understanding have often led to more uncertainty about the future rather than less [10], as the implications of unappreciated processes such as ice-sheet dynamics become clearer.

Set against these challenges, though, are two inescapable facts. Many areas of human endeavour proceed in the face of great uncertainty. Hallegatte [8] cites managing exchange rate risk, energy cost uncertainty and research and development outcomes among others. Thus, the issue is actually one of deploying the correct decision-making frameworks rather than being unable to make decisions under uncertainty, as has been often noted in the past decade [6,10–12].

In addition, not all aspects of uncertainty are equally problematic, and those that are genuinely difficult must not be allowed to inhibit decisions involving the simpler aspects. Notwithstanding the uncertainties, several aspects of climate change are straightforwardly monotonic, leading to only modest levels of uncertainty for many types of decision. The increasing concentration of carbon dioxide in the atmosphere, increasing global average temperatures, sea-level rise (and the general consequences for coastal inundation) and declining ocean pHs are all monotonic changes, with magnitudes that are reasonably certain for the next few decades. Even on longer time frames, it is possible to put high confidence on minimum changes. By contrast, projections of changes of some other elements (such as precipitation or storminess) remain subject to much uncertainty in climate models.

The sense of uncertainty that pervades thinking about adaptation is compounded by the daunting diversity of decisions that could be affected by climate change. However, just as not all uncertainties are equally problematic, nor are all decisions. The growing academic literature on adaptation has canvassed a number of relevant issues, but we contend that these have not yet been synthesized in terms of their implications for practitioners, nor generally embedded in practitioner behaviour.

First, decisions can be mapped with respect to their *lifetime*. Decisions may have a short lead time and short consequence period, such as the choice of which existing wheat cultivar to plant, a decision that can be adjusted every year. Alternatively, they may have a short lead time and long consequences, as with building individual houses, or a long lead time but short consequences, as with

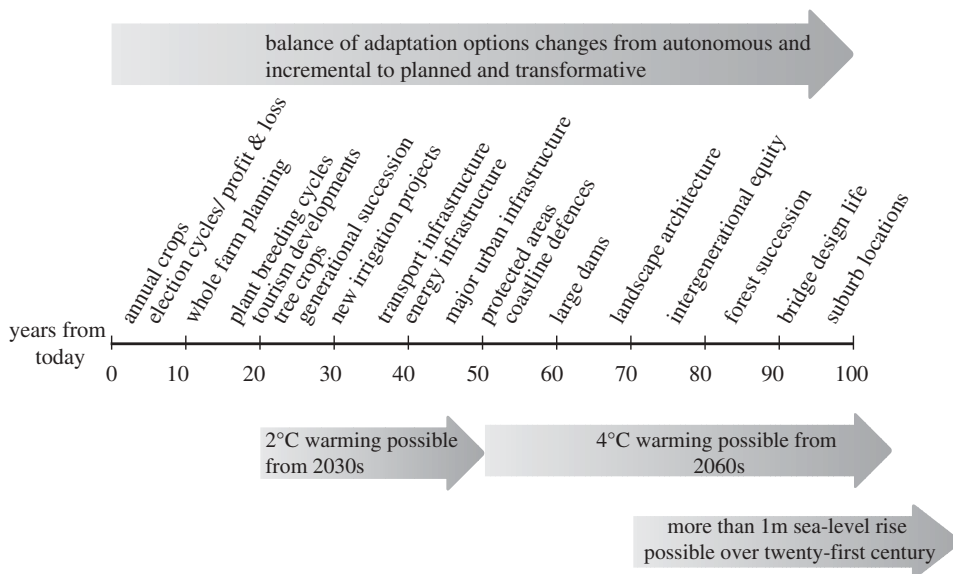


Figure 1. Timeline illustrating the lifetimes (sum of lead time and consequence time) of different types of decisions, compared with the time scales for some global environmental changes, and the changing implications for adaptation. Adapted from Jones & McInnes ([13], fig. 1.4), including items from Hallegatte ([8], table 1). Indicative global temperature rise since pre-industrial times from Betts *et al.* [1]. Indicative sea-level rise over the twenty-first century from Nicholls *et al.* [5].

developing a new cultivar of wheat for planting. Finally, they may have a long lead time *and* long consequences, as with the location of suburbs, which are very hard to move once developed [8,13]. In relation to climate change adaptation, the key issue is the total decision lifetime, as illustrated in figure 1. In general, decisions with a short lifetime need not take account of climate change until it is experienced, whereas decisions with a long lifetime need to consider climate change risks now, regardless of whether the long lifetime is a result of lead time or consequence time or both. Critically, the decision lifetime interacts with the nature of the climate change elements to which the decision is sensitive, as to whether these are changing rapidly or slowly, and with certainty or not.

Second, there has also been a growing understanding of the difference between *incremental* and *transformational* decisions in adaptation [14], building from the ‘resilience’ literature [15]. Transformational change is formally defined as a change in the set of variables that control a system’s functioning [16]. In the present context, incremental adaptation generally implies that adjustments are aimed at enabling the decision-maker to continue to meet current objectives under changed conditions (e.g. changing cultivars to continue farming); whereas transformative adaptation addresses fundamental change in those objectives (e.g. changing out of farming to another land use, or moving an industry to another region). Transformation generally has a long lead time, needed for the players to come to terms with the scale of change. Horrocks & Harvey [17] argue that the ongoing and prospectively greater nature of change in a 4°C world implies

greater attention to a process of what they termed ‘continuous transformation’—ongoing adaptive cycles of incremental and transformational adaptation within a long-term pathway plan. Here, we refer to this as an ‘adaptive pathway’.

Third, adaptation is multi-scaled [18], in that adaptation at household and community levels is embedded within the context set by provincial, national and international governments and industry organizations. Yet, the options open at those higher levels are also conditioned by the state of preparedness at lower scales. The issue of scale is also linked up with the nature of transformation, as intervention is often required from a higher scale to help with the envisioning and implementation of transformative change. Indeed achieving resilience at one scale is often only possible in a time of change by promoting transformation at other scales (e.g. a resilient agricultural sector may require radical changes in the operations of individual farms, just as the resilience of coastal communities may depend on changes in where households live).

Fourth, for more than a decade, a few commentators have been urging a greater focus on risk management and robust decision-making [10,12,19–22]. Yet, the emphasis in climate science continues to be on greater precision rather than on better characterization of uncertainty [10]. Either causing this emphasis or in response to it, many decision-makers perceive the need to know more exactly what is going to happen in the future. The likely persistence of uncertainty requires a change in decision-making style for some classes of decisions—primarily those with longer lifetimes—and possibly a reframing of the problem away from being driven by climate science at all. Robust decision-making approaches, as outlined in Dessai *et al.* [10], identify decisions that are robust across the range of future possibilities, even if they are not precisely optimal for any and as a consequence may be more costly to implement [23]. Scenario-based visioning of the future can encompass drivers of future sustainability, which are far more diverse than climate alone, such as those used in the Millennium Assessment [24].

Fifth, there is a small but genuinely difficult class of decisions where risk-hedging is necessary. For example, Steffen *et al.* ([25], box 9) argue that this is the case in post-fire management in the Victorian alpine forests. Here, the trees that will provide nesting hollows and microclimates for many other species in 120 years’ time need to be established now; yet in 120 years different tree species are likely to be successful under different futures. In this case, the only option is to consider risk-hedging by promoting the establishment of different species in different parts of the same landscape, in the certain knowledge that some of them will turn out to be the wrong choices. The fact that some adaptation decisions may be so awkward needs recognizing, particularly as the likelihood of a 4°C world increases. However, this category of decisions should not be allowed to obscure the fact that the majority of decisions is less awkward.

Most of these observations have been recognized in the academic literature for at least a decade, but have not yet been integrated in a form that resonates with and informs practical decision-making on adaptation. On the contrary, in our experience of interacting with practitioners, much of the language used about adaptation emphasizes once-off, small adjustments to existing practice in which objectives are unchanged but pursued with climate change taken into account. In this mental model, adaptation is the means to ensure that we can

continue what we are currently doing into the future, and the possibility that transformation might be needed is largely unaddressed. Strategies usually target building capacity, taking incremental steps and ‘mainstreaming’. The emerging prospect that the world will face at least 4°C global warming, as soon as the 2070s under some projections [1], demands that this approach be reassessed. If a 4°C world eventuates this century, many current actions are failing to meet the challenge. Adger & Barnett’s [7] concern about maladaptation will be realized if we invest in activities that prove, at best, costly and pointless if a 4°C future materializes, and at worst may have prevented more transformative measures.

3. Barriers to adaptation for a 4°C world

The prospect of 4°C global warming within the lifetimes of people born today is confronting, not least because there are many barriers to successful adaptation [7]. Although urgently needed, a comprehensive assessment of these is beyond this paper. However, we can consider those barriers that interact particularly significantly with the issues raised in §2, in order to unlock decision-making in the face of the 4°C challenge.

(a) Psychological and social barriers

Humanity’s ability to adapt physically to a 4°C world will depend in part on how well people adapt psychologically. Governments, other organizations and individuals will not undertake adaptation activities until they accept the need to do so. Most adaptation literature assumes that accepting the need to act follows from demonstrating the damage that will flow from failing to act. This makes the unwarranted assumption that humans respond to threats with adaptive coping strategies rather than with psychologically maladaptive ones or forms of denial [26].

There is a wide range of cognitive strategies that individuals (and groups) may employ to avoid fully or partially accepting the possibility of unpleasant futures and the need to act now. They are briefly described in table 1. Many of these are promoted by the sense that future climate changes are uncertain, distant or overwhelming, all characteristics of the current narrative around adaptation. Individuals and perhaps cultures have to pass through the stages of denial, notional acceptance but failure to accept any personal responsibility for acting, to finally acting on such issues, although this passage is by no means necessarily a smooth one [26,27].

The way individuals cope with a 4°C world will be influenced by how societies and their institutions respond to the new environment. If only a minority are pursuing adaptive coping strategies while others are engaged in denial or maladaptive strategies, the former may feel isolated and disempowered, and governments and other institutions will be under less pressure to undertake adaptation measures, particularly those with long lifetimes. Thus, facilitating the majority to take at least small steps on an adaptation pathway may overcome this paralysis. Crompton & Kasser [28] propose two types of response to encourage governments, non-government institutions and professional organizations to

Table 1. An analysis of psychological strategies for responding to the prospects of severe climate change (after [26]).

types	strategies	brief description
denial strategies	active denial	resolves cognitive dissonance by actively rejecting scientific claims
	casual denial	avoiding exposure to and dismissing uncomfortable facts with the assistance of narratives about scientific uncertainty or errors
maladaptive coping strategies	reinterpreting the threat	by making its scale seem smaller or its timeframe distant, people ‘de-problematize’ the threat
	diversionary strategies	appropriate thoughts and actions are displaced by positive but trivial actions (such as installing low-energy light bulbs) or by pleasure-seeking
	blame-shifting	responsibility is disavowed by blaming others for the problem. For example, China has become a popular scapegoat for global warming
	indifference strategies	deliberate apathy can reduce short-term pressures but may exact a heavy psychological toll
	unrealistic optimism/wishful thinking	‘benign fictions’ lead us to predict what we would prefer to see. Such unrealistic optimism becomes maladaptive when healthy illusions refuse to respond to external evidence and become delusions
adaptive coping strategies	expressing and controlling emotions	feelings of anger, despair and hopelessness are natural in the circumstances. Emotion-focused coping requires that we express these feelings but do not become ‘stuck’ in them
	problem-solving	finding out more about a threat may alleviate anxiety. If knowledge leads to action, working with others helps establish a sense of control
	new value orientation	considered reflection on death has been shown to promote life goals that are less materialistic and more pro-social

promote adaptive coping strategies: simply publicizing and encouraging adaptive strategies while gently pointing out maladaptive ones; and, promoting value shifts in society towards those that are more sympathetic to cooperation and recognition of intrinsic, rather than materialistic, values. Naturally, these are only two of many necessary contributions.

(b) Cognitive responses to uncertainty

A specific aspect of psychological barriers arises from our cognitive capabilities. Research demonstrates that individuals and organizations struggle to deal effectively with uncertainty. This is a well-recognized barrier to better decision-making in relation to climate change, even though there are many risk-management tools and techniques (see review in [29]) available to help policy-making under such conditions. As the analysis of climate adaptation becomes

more sophisticated, there is a move towards a more explicit treatment of uncertainty through, for example, probabilistic scenarios. However, even when the outcomes and probabilities of an event are known ('risk'), this does not mean that decision-making is any easier or any more 'accurate' or that a risk-based approach to decision-making will necessarily lead to the effective management of uncertainty.

As individuals, we have a tendency to make judgements about future events based on our experience of past events, particularly those that evoke strong feelings or have occurred recently. Although a more 'deliberative' approach to processing information for decisions can be learned, this generally requires a high degree of conscious effort. The affective system of decision-making tends to prevail when there is uncertainty or disagreement over a decision. We tend to map 'uncertain and adverse aspects of the environment into affective responses' based on our past experience and feelings ([30], p. 105). Events in the future are considered abstract, so that people resist scientific conclusions if the findings are considered 'unnatural' or unintuitive [31]. When people are making decisions based on their 'affective' mechanism, a disjunction between measures of risk is likely, and this will play an important role in defining the scope for action [30–32]. A clear framework for making decisions in the face of uncertainty could reduce the level of cognitive processing required to tackle the problem, and at least make the processing of uncertainty more explicit and transparent. Indeed, experience from communicating uncertainty in weather forecasts, for example, suggests that it is necessary to communicate why information is uncertain, what in particular is uncertain and why it is important [33]. The framework presented in §4 is a starting point for such an approach.

The cognitive limitations of individuals often extend to organizations and institutions, even though these have the potential to act far more effectively than individuals. The process of organizational decision-making generally has little to do with 'intentional, future orientated choice' but is more a consequence of less formal influences that can spread through an organization like 'measles' ([34], pp. 97–106). Decision-making is tied closely to issues of power, political behaviour [34,35] and 'positioned practices' within organizations [36]. Research within larger organizations has found considerable evidence that decision-making cannot be easily influenced through tools and frameworks or the provision of information. Langley ([37], p. 600) found evidence that formal analysis (defined as 'written documents reporting the results of some systematic study of a specific issue') generally played little role in informing decision-making, and was conducted partly to provide information but also for symbolic purposes. For example, instead of leading to a change in strategy or direction, managerial tools may be used to legitimize or enhance the organization's reputation with legislators [36], and uncertainty can become an unwitting tool in these sorts of responses.

A clear categorization of types of decisions will not in itself remove institutional constraints but can provide a foundation for those seeking better outcomes within the institution—'facilitate the infection of measles' as far as the kinds of decision that need to be considered when facing a 4°C world. However, organizational fads are not enough—the role of the government is still crucial in influencing risk-management uptake and practice (e.g. [38–40]), as we now explore.

(c) Governance structures and institutions

In addition to psychological and cognitive constraints, structural aspects of institutions lead to other barriers to effective adaptation. Often these can only be resolved by decision-makers at higher levels of governance (e.g. national governments may only become willing to act on handling refugees within their country once a global agreement is decided) or by a significant change in what is asked of the institutions by decision-makers at a grassroots level (e.g. voters changing their aspirations sufficiently that a Western democratic system has to follow them). In the absence of these drivers for action, the national scale can fall into what has been termed the ‘climate change governance trap’ ([41], p. 683): because of the scale of the climate change ‘problem’ it is perceived to be the responsibility of national politicians and policy-makers, who in turn are unwilling to impose potentially necessary, but unpopular, measures because of the electoral cycle.

This problem is significant since it is usually government that is responsible for long-lifetime decisions, such as major infrastructure and urban planning. While we are seeing the proliferation of policies, guidelines, committees and partnerships established to address adaptation, it is still unclear how these various governance structures will interact across scales to enable adaptation. To date there is limited research in this area, although recent evidence of progress in the UK [40] is encouraging. Other case studies have found that existing policies may have a negative impact on adaptation at lower levels of governance [42], and a mismatch may exist between local responsibilities and resources needed for implementation [43].

One political and institutional barrier to adaptation to high-end warming scenarios is peculiar to the climate change issue. This is the sense that it is not acceptable to consider adaptation to more than 2°C of global warming, because it is seen to weaken the negotiating position on emission reductions (e.g. [44]). Given the current failure of negotiations on emissions reduction, this attitude needs to be challenged as a matter of precaution.

(d) Removing the barriers

These situational factors highlight the difficulty of promoting adaptation action. They also help explain why there is so much focus on framing adaptation as capacity building, incrementalism and mainstreaming; it is difficult to make a case for adaptation among all the other signals competing for limited resources.

Despite these constraints, there are examples of institutions starting to look at the implications of more than 2°C of global warming in sensitive sectors that have long-term planning perspectives. Recently, the Institute of Mechanical Engineers [45], the Royal Institute for British Architects and the Institute of Civil Engineers [46] in separate policy-oriented reports have considered the possible future of adaptation in the UK especially in light of sea-level rise; studies in Australia have explored the implications for natural ecosystem management [25] and coastlines [47]. While the reports differ in focus and scope, the recommendations converge: countries must be prepared to consider and plan for radical changes to people’s way of life, including considering the long-term viability of ‘many settlements, transport routes and infrastructure sites, planning for either their defence or ordered abandonment’ [45].

These rare examples contrast with the entrenched tendency to make incremental adjustments. Simply presenting people with the prospect of a 4°C world is unhelpful and disempowering unless the complexity of dealing with the thousands of decisions that might be affected by climate change can be simplified. In response, therefore, we argue that a systematic approach is required to reduce the complexity of the adaptation decision-making environment at just the time when that complexity seems to be growing with the increasing expected rates of change. Such a systematization needs to show that the future is less uncertain than often supposed. It also needs to show how decisions are not all equal: complex decision-making can be structured into manageable and actionable steps for which there are well-trodden analytical pathways, even in the face of uncertainty. We now turn to the beginnings of such an approach.

4. Responses under diverging climate futures

Global climate models, driven by a range of emissions scenarios, are used to define the envelope of uncertainty surrounding future climate change (e.g. [1]). This envelope increases over time (figure 2), resulting in increasingly divergent pathways that may need to be taken into account in adaptation planning. Even those aspects of climate change that increase monotonically over time are subject to some uncertainty with respect to rates of change. Figure 2 shows that the lifetime of the adaptation decision is a key factor determining whether planning needs to address a relatively certain set of changes, or allow for diverging, and potentially very different, climate futures.

We argue in this analysis that the interactions between three key factors determine the treatment needed for different adaptation decisions (table 2); and that these three factors help to elucidate when the other issues raised in §2 become important. The three factors are

- (i) The *decision lifetime*, which may vary from *short* to *long* (figure 1): longer lifetime decisions must deal with a more widely divergent set of futures than short-lifetime decisions (figure 2), although whether this matters depends on the other two factors.
- (ii) The nature of *driver uncertainty* for drivers of relevance to this decision: whether the driver is mainly *monotonic* or *indeterminate*. Decision drivers such as sea-level rise, mean temperatures, ocean and atmospheric CO₂ chemistry, and derived characteristics such as the likelihood of heat waves, length of growing seasons, or frequency of coastal inundation extremes, are essentially *monotonic* over at least the next 50–100 years in most places, whereas changes in rainfall, numbers of cyclones, relative humidity and the net effects of changing cloudiness and warming on numbers of frosts currently remain *indeterminate* in many regions. Of course, if the climate does recover, the monotonic changes will cease, but this is beyond the timeframe of most decisions at present. For monotonic drivers, uncertainty lies mainly in timing; for indeterminate drivers, even their effect is uncertain. Whether this in turn matters depends on the nature of the adaptation response.

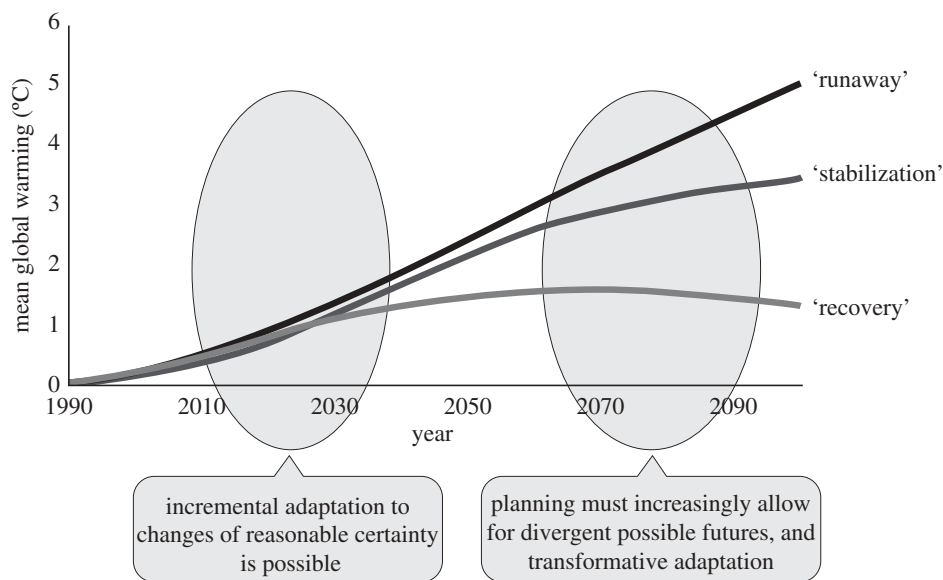


Figure 2. Future projections of climate change diverge over time as social uncertainty outstrips scientific uncertainty, with changing implications for adaptation. Adapted from stylized projections based on ('runaway') the A1FI+ scenario in Garnaut ([55], fig. 4.5), and ('stabilization') the MEP2030 reference and ('recovery') MEP2010-overshoot scenarios updated from Sheehan *et al.* ([56], fig. 8c; R. N. Jones (2010), personal communication).

(iii) The *adaptation response* in a decision may take one of three forms, which we characterize in terms of their *type* and *extent*.

- The same type and extent whatever the uncertainty in the drivers—this is the rare but precious 'no regrets' decision, which may as well be taken regardless (subject to having a positive benefit–cost ratio). For example, it has been observed that the core rules for systematic selection of conservation reserves—the so-called CAR (comprehensive, adequate and representative) principles—remain the same under any future climate, since representing all environments in the reserve system is most likely to provide habitat for the maximum number of species even if these no longer occur in their current locations [48].
- The same type but a different extent, depending on the uncertainty in the driver. Examples are the engineering temperature tolerance to be adopted for an electricity transformer in the face of an increasing risk of heatwaves and the height of a sea-wall relative to different sea-level rises.
- A different type (and extent) in different future scenarios. For example, coastal defences in the form of barriers make sense up to a point, but beyond that point these will be maladaptive and coastal retreat policies may be preferred. In a smaller class of decisions, fundamentally different strategies must be chosen today according to different futures, as in the case of post-fire management in the Victorian alpine forests noted above [25].

Table 2. Implications of different combinations of decision lifetimes, driver uncertainty type and adaptation response types for decision-making strategies and tactics under diverging climate futures.

decision lifetime, relative to rate of climate change	type of driver uncertainty	type of adaptation response options	characteristics of decision-making about risk	some options available to reduce decision risk ^a
1 short- or long-term	monotonic or indeterminate	same type and extent of response under all scenarios	'no regrets': normal business planning to implement response cost-effectively	monitor to ensure no regrets response still suffices
2 short-term (easily reassessed)	monotonic or indeterminate	little divergence between scenarios over short-term means considering only one set of responses	ongoing, incremental adaptation in line with pace (and direction) of change	monitor rate of change to provide advanced warning of thresholds and need for transformation
3 long-term (implications may last for 50–100 years)	monotonic	same type but different extent of response for different scenarios	precautionary risk management: use benefit–costs analysis to determine appropriate level of response now	reassess regularly to ensure rate of change still in risk envelope; real options, safety margins, shortened decisions
4		different type (and extent) of response for different scenarios	risk-hedging against alternative futures (with gradual transfer of resources as uncertainty diminishes); act now, given monotonicity	high likelihood of need for transformation at some stage; reversible options, soft adaptations; shortened decisions often impossible
5	indeterminate	same type but different extent of response for different scenarios	robust decision-making paradigm in the face of uncertainty about direction of change	monitor change to identify if conditions are moving outside 'robust space'; reversible options, safety margins, soft adaptations, shortened decisions all useful
6		different type (and extent) of response for different scenarios	risk-hedging against alternative futures (with gradual transfer of resources as uncertainty diminishes); delay acting if possible	hardest combination: real options most likely to pay off if possible; likely to need support from higher levels of governance

^aAbbreviated terms for some options from Hallegatte [8] and Dobes [49]: 'real options'—conscious decision delay where benefits of improved information exceed risk of costs of delay; 'reversible options'—favouring reversible and flexible options; 'safety margins'—buying safety margins in new investments (e.g. bigger foundations pre-adapted to higher structures that are not yet built); 'soft adaptations'—promoting changed behaviours and arrangements over physical infrastructure (e.g. reduced household water demand rather than a new dam); 'shortened decisions'—reducing decision time horizons (e.g. housing with a short lifetime) within a long-term view.

These three factors—decision lifetime, the nature of driver uncertainty and the form of adaptation responses—combine to require different approaches to risk management. They also highlight where the various risk mitigation tactics outlined by Hallegatte [8] are most likely to be applicable, as well as how to think about transformative as opposed to incremental adaptation now and at what institutional scale of decision-making. We now illustrate some of these implications summarized in table 2.

First (row 1 of table 2), where the adaptation response (same type and extent regardless of driver uncertainty) is no regrets, there is no reason to complicate decision-making any further. This is true for both short- and long-lifetime decisions, although decision-makers are probably already dealing successfully with the short-lifetime cases. We therefore devote no further space to these, other than noting that ongoing monitoring and reassessment are always required to ensure the decision space has not changed.

Second (row 2 of table 2), while short-lifetime decisions do face uncertainty, in general, future scenarios do not diverge much over the coming 10 years. In both monotonic and indeterminate cases, incremental adaptation is appropriate, reacting to change as it emerges. Where adaptation responses are of the same type, whether the drivers are monotonic or indeterminate, the extent of response can be gradually adjusted over time (e.g. gradually altering the choice of crop cultivar to plant). However, it is important to establish monitoring processes that provide plenty of lead time for when a more transformative change may be needed (e.g. when the regional climate moves outside the tolerance of any available cultivars), and this monitoring may require the involvement of a higher level of governance. Where adaptation responses may be of different types as change increases, there is likely to be a strong justification for deliberately delaying decisions, applying the concepts of real options [49].

However, our main focus here is on long-lifetime decisions, given the increasing prospects of a 4°C world. Four combinations of driver uncertainty and adaptation response remain (rows 3–6 of table 2), and each requires different treatment.

- The key drivers may be monotonic, necessitating a variable extent of a fixed type of response; this is true for many aspects of setting design performance criteria and risk margins in engineering guidelines in the face of higher temperatures, and for standards such as concrete corrosion (e.g. [50,51]). For these decisions, risk management should adopt the precautionary principle, choosing a response extent (e.g. a new design extreme) through traditional benefit–cost analysis against the uncertainty in timing of change. Risks can be reduced by allowing extra safety margins where this is cheap to do, or deliberately shortening the lifetime of infrastructure where this is feasible and cost-effective.
- The key drivers may be monotonic, but such that different levels of change necessitate fundamentally different types of response. Examples include implementing incremental coastal defences up to some level of sea-level rise but then needing to consider planned retreat, or gradually adapting farming system practices and cultivars to a drying climate but eventually having to change land use (or location) all together. The example of post-fire management in the Victorian alpine forests given alternative future regional temperatures for trees establishing now, as noted above [25], also

falls into this category. Risk-hedging in space against these alternatives (i.e. promoting different actions in different places) is an option to ensure that at least some coastal settlements or farming systems or conservation reserves are ready for whichever future eventuates. Over time, there can be a planned process through which resources are shifted towards whichever option looks more likely. This combination has certainty about direction of change, so that early action is likely to be economically sensible. As these examples show, this option is often associated with the need for early consideration of transformative adaptation. Risks can be reduced by adopting reversible options and soft adaptations that can be withdrawn if the future they were hedging against does not seem to be emerging. Early planning for transformation so that initial responses are compatible with this eventuality is also desirable. This will often require the intervention of higher levels of governance.

- The key drivers may be indeterminate, but nonetheless demand responses of a consistent type. Examples include the uncertainty over water supplies for many cities where rainfall may rise or fall. The response is still to manage supply against demand (usually in the context of increasing population), but the value of investing in expensive new infrastructure like dams or desalination plants is uncertain. Often risk management demands a robust decision-making paradigm, as illustrated for water utilities in California by Dessai *et al.* [10], making decisions that withstand alternative futures even if they are not optimal for any one of them. Ongoing re-assessment of change then allows the response to be finessed over time. Risks can be reduced in many ways. For water, risk can be reduced by investing in soft adaptations such as reducing water demand ahead of major infrastructure decisions. Where infrastructure investments are necessary, building in cheap safety margins or shortening the life of the infrastructure may be desirable.
- Finally, the key drivers may be indeterminate with very different response types needed under different futures. This is the hardest combination to deal with, and one where the possibility of consciously delaying the decision ('real options' analysis; e.g. [49]) is most likely to be cost-effective. An example is a major irrigation district that faces uncertainty in water futures. Even if rainfall decreases, increased storm intensity may result in more run-off and water storage. More irrigation water in the future may require agricultural expansion to help with food security whereas less water might mean the region moving out of agricultural altogether, decisions with major implications for investment in regional infrastructure. This category of decision is not common, although it will become of increasing concern as greater levels of global warming are contemplated.

We can only initiate this analysis here, but we argue it is a profoundly important and urgent issue to pursue, and to convert into guidelines for practice. Moving through table 2 from top to bottom, we anticipate a trend from adaptation options that could be seen as minor adjustments to 'business as usual' towards more transformative options. Where diverging climate futures require very different responses, there is likely to be at least one set of options that is transformative, and this possibility can be seen much more starkly through

consideration of a 4°C world. By contrast, wherever adaptation decision-making (whether for short- or long-lifetime decisions) is currently conceptualized only as an issue for conventional business planning (i.e. designed to implement responses at the most cost-effective moment) the emphasis will be on building capacity and limited horizons, with little consideration of the effectiveness of actions against a dynamic and changing risk landscape. This mindset (which is legitimate and efficient for some decisions) is unlikely to be able to visualize the potential need for transformative adaptation, nor to be able to implement it effectively and efficiently. Evidence shows that many current societal adaptations are by-products of other activity [40], and so are unlikely to address the implications of a 4°C world.

Focusing on adaptation as a continual incremental process of adjustment is a useful means of helping decision-makers relate future climate change to current concerns and planning horizons. It also provides an easy means of ‘selling’ adaptation to stakeholders and thereby building capacity for future decisions. However, the approach does not cope well with larger climate changes or the possibility of very different responses under diverging climate futures.

Focusing on adaptation as a process that may involve ‘continuous transformation’, is more appropriate for decisions that may last into a 4°C world, although incremental steps may be required within the transformative approach. Flexible decision pathways that identify a wide range of adaptation options suitable for different extents of climate impact over different timeframes can provide the bridge between the incremental approach required for the pragmatic reasons of integrating with existing planning and management protocols, and the ability to learn and re-orientate as the future unfolds. Although pre-dating our analysis, the proposed flood risk-management plan for the Thames Estuary out to 2100 was developed through such an approach, as the following case study shows.

(a) Case study: Thames Estuary 2100

London and the Thames Estuary have always been subject to flood risk. Current high levels of protection are justified by the high value of the assets at risk. The Thames Barrier is one iconic feature of the current flood risk-management scheme. While the Barrier’s original design allowed for some sea-level rise, it did not make any specific allowance for the range of possible climate changes. The Environment Agency set up the Thames Estuary 2100 project (‘TE2100’) to develop a Flood Risk-Management Plan for London and the Thames Estuary for the next 100 years [52,53].

Retrospectively, it is clear that the project was tackling a set of linked, long-lifetime decisions, mainly facing a monotonic driver in sea-level rise, but with a suite of adaptation responses available that varied from incremental (e.g. raised defences) to transformational (e.g. a completely new barrage location). TE2100 pioneered an approach to identifying adaptation options that specifically addressed the uncertainties in projections of future climate and development along the Thames River. The outcome was a set of adaptation options linked to different extents of climate change (see ch. 7 in [54] for further details); figure 3 illustrates the options produced in 2007. Each option consists of a decision pathway through the century to deal with different water-level rises. The pathway

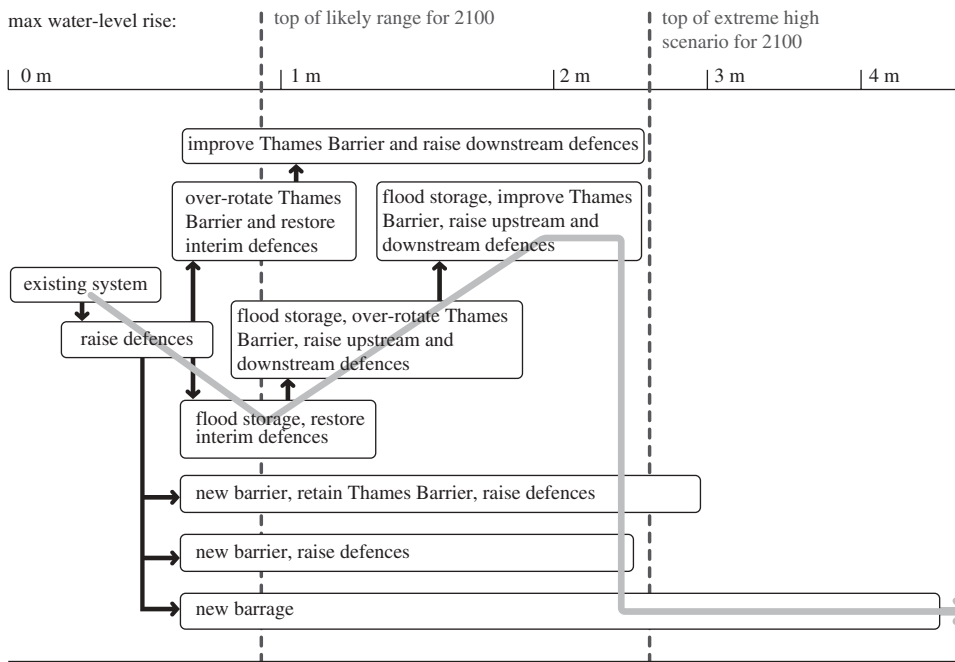


Figure 3. Adaptation options and a decision pathway for flood risk management in the Thames Estuary. The dashed lines indicate the extents of water-level rise projected for 2100 under different scenarios. The thick grey line shows one possible pathway for introducing different options to address rising water levels. This type of flexible pathway shows how incremental and transformative options can be combined. Adapted from Lowe *et al.* ([54], fig. 7.4). Boxes indicate measures for managing flood risk indicating effective range against water level.

can be adapted to the rate of change that eventuates. Planning decision lead times and consequence times created challenges, which were also explicitly addressed, with the timing of key decision points identified along the trajectory.

The TE2100 options were the subject of extensive stakeholder engagement, and subsequently formed the basis of the draft plan awaiting UK government approval in early 2010. In line with UK government guidance on climate change at the time, the plan focuses on a potential 1 m water-level rise over 100 years. It identifies the appropriate pathway to address that level of change, with actions for the short (to 2034), medium (to 2069) and long term (from 2070). Thus, the plan itself defines a set of incremental adaptation measures, rather than explicitly documenting the complexity of the underlying research. However, three important elements distinguish this approach from previous incremental analyses.

- Shorter term decisions are nested within a longer term framework that explicitly identifies key thresholds and options for dealing with much larger extents of change. (For example, 10 indicators for change will be formally monitored to identify if or when a switch to alternative options may be needed.)
- The plan allows for flexibility on the timing of introduction of different options and interventions, and the ability of the plan to change between options, based on the monitoring programme.

- Detailed guidance is provided on how the recommendations contained in the plan should be applied in the event that more extreme change is realized; for example, if it becomes necessary to divert to an alternative adaptation pathway. This guidance also shows how lead times for major interventions need to take account of any such changes, and is underpinned both by the identification of key decision points and by the inclusion of the monitoring and review cycle.

The Thames Estuary case study provides one example of how adaptation decisions with long lifetimes can be assessed and framed in a way that can be absorbed in strategic planning. This includes, for example, safeguarding land allocations for future options, and considering whole of life costs for structures to justify higher initial costs that may provide benefits in terms of future flexibility, such as providing foundations now which could take higher barriers in future more cheaply than complete rebuilding.

Long-term development of physical (and ecological) infrastructure, and the organizations, institutions and policies that support it, usually occurs as the cumulative effect of many shorter term decisions (not least because these are demanded by political and financial cycles). The ability to ‘nest’ such short-term decisions within a longer term framework, which appropriately considers a range of possibly diverging climate futures, is likely to be critical in planning adaptation for a 4°C world. From this can emerge ongoing adaptive pathways that accommodate both incremental and transformational adaptation.

5. Conclusions

Given the prospects for a 4°C world, adaptation needs to be reconceptualized away from the incremental handling of residual risk to preparing for continuous (and potentially transformational) adaptation. One effect of contemplating projections with 4°C and more of warming is that the range of futures for planning long-lifetime decisions becomes greater and more uncertain, at least at first sight. These features are known to exacerbate psychological, cognitive and institutional barriers to action. We therefore show how it is possible to systematize an approach to the resulting decision-making challenges in ways that have the potential to reduce the disempowering impacts of uncertainty, by disaggregating the decision-making process into actionable steps that use well-established methodologies. To do this, we have shown how the lifetime of a decision interacts with the different types of uncertainty and the nature of potential adaptation responses. The resulting six categories of decision pathways require distinctive risk-management strategies and tactics, all of which are individually well understood.

Developing these ideas leads naturally into nesting decisions in scale, in terms of both time (thus creating adaptation pathways with continual re-evaluation) and process (such that more incremental and short-term decisions may be embedded within longer term transformational choices that define key decision points for reappraisal over time). These developments are well illustrated by the Thames Estuary case study, but require more systematization and absorption

into decision-making at all levels of society. We have sought to advance this systematization here, recognizing that this can be developed and enriched much further.

This systematization aims to minimize the potential effects of various psychological, cognitive and institutional barriers on the decision-making process. While we have made the case that this outcome should follow, we present it as a hypothesis now more able to be tested with practitioners in the future. These barriers will not be entirely alleviated by a logical process alone and our approach needs translating and framing for any given institutional context. In practice, decisions about responding to climate change must be taken in the context of many other social and environmental changes, and may have trades-offs related to other decisions aimed at the more general achievement of sustainability. The further development and uptake of these ideas would thus benefit from building a set of practical examples that people can observe, a process that can be supported by governments at all levels. In this regard, the gradual emergence of case studies such as those noted in this paper is encouraging, and their systematization into frameworks such as that proposed in this paper to guide decision-makers in practice is an urgent task.

The work of M.S.S. reported in this publication was supported by CSIRO Climate Adaptation Flagship. L.H. and A.H. were supported by AEA. We are grateful for the comments of Sarah Park, Andrew Ash, Mark New and three anonymous reviewers. We also thank Tim Reeder of the Environment Agency for sharing his insights and experience of the TE2100 project.

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