Global Environmental Change 19 (2009) 240–247

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Strategies to adapt to an uncertain climate change

Stéphane Hallegatte [a,b,*]

[a] Centre International de Recherche sur l'Environnement et le Développement (CIRED), 45bis Av. de la Belle Gabrielle, F-94736 Nogent-sur-Marne, France
[b] Ecole Nationale de la Météorologie, Météo-France, Toulouse, France

ARTICLE INFO

Article history:
Received 6 July 2008
Received in revised form 24 November 2008
Accepted 4 December 2008

Keywords:
Climate change
Adaptation
Uncertainty

ABSTRACT

Many decisions concerning long-lived investments already need to take into account climate change. But doing so is not easy for at least two reasons. First, due to the rate of climate change, new infrastructure will have to be able to cope with a large range of changing climate conditions, which will make design more difficult and construction more expensive. Second, uncertainty in future climate makes it impossible to directly use the output of a single climate model as an input for infrastructure design, and there are good reasons to think that the needed climate information will not be available soon. Instead of optimizing based on the climate conditions projected by models, therefore, future infrastructure should be made more robust to possible changes in climate conditions. This aim implies that users of climate information must also change their practices and decision-making frameworks, for instance by adapting the uncertainty-management methods they currently apply to exchange rates or R&D outcomes. Five methods are examined: (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 long-term prospective; and (v) reducing decision time horizons. Moreover, it is essential to consider both negative and positive side-effects and externalities of adaptation measures. Adaptation–mitigation interactions also call for integrated design and assessment of adaptation and mitigation policies, which are often developed by distinct communities.

1. Introduction

There is an increasing agreement that many decisions already need to take into account climate change. Obviously, many decisions have only short-term consequences or are only weakly climate sensitive. A factory that produces electronic devices has a lifetime of less than a few decades, and climate conditions will not be that different over this timescale. Also, such a factory is not highly sensitive to climate conditions, provided that it is not built in a flood plain or along a coastline.

But many decisions come with a long-term commitment and can be very climate sensitive. Examples of such decisions include urbanisation plans, risk management strategies, infrastructure development for water management or transportation, and building design and norms. These decisions have consequences over periods of 50–200 years. Urbanisation plans influence city structures over even longer timescales. These kinds of decisions and investments are also vulnerable to changes in climate conditions and sea level rise. For example, many building are supposed to last up to 100 years and will have to cope in 2100 with climate conditions that, according to most climate models, will be radically different from current ones. So, when designing a building, architects and engineers have to be aware of and account for the future changes that can be expected. Milly et al. (2008) demonstrate why water management cannot keep using the stationarity hypothesis in its investment decisions. Since they report that more than US$ 500 billion are invested every year in this sector, the implementation of new practices cannot be delayed. Also, Nicholls et al. (2007) showed that, in 2070, up to 140 million people and US$ 35,000 billion of assets could be dependent on flood protection in large port cities around the world because of the combined effect of population growth, urbanisation, economic growth, and sea level rise. But previous coastal defence projects (e.g., the Thames Barrier) have shown that implementing coastal protection infrastructure typically has a lead-time of 30 years or more. Also, urbanisation plans are very efficient to influence flooding risk, but they can do so only over many decades. This inertia suggests that action must begin today to protect port cities and to manage flood risk for impacts expected by the middle of this century. To be efficient, however, this action has to take into

* Correspondence address: Centre International de Recherche sur l'Environnement et le Développement (CIRED), 45bis Av. de la Belle Gabrielle, F-94736 Nogent-sur-Marne, France. Tel.: +33 1 43 94 73 73; fax: +33 1 43 94 73 70.
E-mail address: hallegatte@centre-cired.fr.

0959-3780/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.gloenvcha.2008.12.003

Table 1
List of sectors in which climate change should already be taken into account, because of their investment time scales and their exposure to climate conditions. In this table, exposure is estimated empirically by the author.

Sector	Time scale (year)	Exposure
Water infrastructures (e.g., dams, reservoirs)	30–200	+++
Land-use planning (e.g., in flood plain or coastal areas)	>100	+++
Coastline and flood defences (e.g., dikes, sea walls)	>50	+++
Building and housing (e.g., insulation, windows)	30–150	++
Transportation infrastructure (e.g., port, bridges)	30–200	+
Urbanism (e.g., urban density, parks)	>100	+
Energy production (e.g., nuclear plant cooling system)	20–70	+

account sea level rise and possible changes in storminess linked to climate change.

Table 1 proposes a list of sectors in which decisions should already take into account climate change, because they involve long-term planning, long-lived investments and some irreversibility in choices, and are exposed to changes in climate conditions.

Fortunately, there has been a significant rise in awareness worldwide about climate change. The positive outcome of this shift in awareness is that many architects, urban planners, water managers, and other planners are now concerned about how climate change will influence their activities. Laboratories working on climate change are well aware of this shift, as demands for information about future climates are becoming more frequent.

Even though this new awareness is very positive, it is hardly enough. Climate change represents more than a just change in climate conditions. For decision-makers, climate change represents, more importantly, a dramatic increase in uncertainty. In the past, the climate parameters pertinent to most activities could be observed and measured. In presence of well-posed objectives, statistical analyses and optimization algorithms were able to produce "best" designs as a function of known climate conditions (e.g., dike heights as a function of the return time of certain storm surges, or building characteristics as a function of typical temperature levels). In the future, however, substantial climate uncertainty makes such methods more difficult to apply. It seems, therefore, that new decision-making methods have to be developed. This article discusses the issues we face in the development of these much needed methods.

The main contributions of this paper are threefold. First, we discuss the role of uncertainty in adaptation strategies, which has already been discussed in the literature (see, e.g., Adger et al., 2007), but much less than the role of uncertainty in mitigation decisions (e.g., Yohe et al., 2004; Lempert and Collins, 2007). Second, we discuss practical adaptation strategies that can be implemented with anticipation in spite of the uncertainty, completing previous papers on this point (e.g., Nicholls and Leatherman, 1996; Fankhauser et al., 1999). We also provide examples of application of these strategies in various locations, showing that many actors are already taking action. Finally, we call for the development of innovative adaptation strategies able to cope with the uncertainty on future climates, and for more involvement of climate information end-users, because these strategies cannot be developed without them.

2. Long-term investments and climate uncertainty

When designing climate-sensitive investments, like water management infrastructures, engineers are used to turning to national meteorological services that are often responsible for collecting weather data and creating climate data, i.e. statistical analyses of weather conditions. These climate data include simple information, like average annual temperature and precipitation, and sophisticated ones, like statistics of meteorological extremes (e.g., heavy-precipitation probabilities). These climate data are then used, among many other parameters, by engineers to design infrastructure and buildings, by insurance companies to calculate premiums and capital needs, by farmers to choose crops and equipment, by national governments to assess energy security requirements, by local authorities to assess building permits, etc.

Now that it is widely believed that climate change will modify the statistics of these climate variables, these users turn to climate modellers to produce the equivalent of these observed climate data, but for the future climate. This approach, however, will not work, as explained below.

The first problem arises from the speed of the expected changes. In Hallegatte et al. (2007), the authors proposed a measure of climate change using "climate analogues". They showed, for instance, that the future climate of Paris in 2080 under the SRES A2 scenario could become the current climate of Cordoba (South of Spain). This would mean that a building built now to last 80 years would have to face, over its lifetime, the climate of Paris, then a warming climate, up to the current climate of Cordoba. For an architect, it is not more difficult (nor more expensive) to design a building adapted to the climate of Cordoba than to the climate of Paris. But it may be more difficult (and more expensive) to design a building adapted to both, i.e. able to be comfortable around the year, cheap to heat in winter, and cheap to air-condition in summer, in this large range of climate conditions (see for instance Roaf et al., 2005).

So, even when a stabilized climate change would eventually reduce the need for investment (e.g., thanks to reduced needs for heating in cold regions), an immediate impact of the ongoing climate change could (and should) be the additional cost of designing new infrastructure to be adapted to the full range of future climates instead of only the current one. Paying this price now, indeed, may be the only way of avoiding large building and infrastructure retrofitting costs in a few decades.

But this issue is only a tiny part of the problem. More problematic is the uncertainty in future climate. Ideally, indeed, climate models would be able to produce climate statistics for the future, from today to when a building or when infrastructure will need to be replaced. This is the information that engineers need to optimize future investments. Unfortunately, two problems make it impossible to provide the equivalent of historical climate data for future climates. First, there is a scale misfit between what can be provided by climate models and what is needed by decision-makers. Second, and most importantly, climate change uncertainty is significant. The first problem can be mitigated by downscaling techniques (e.g., using regional models with limited domains or statistical relationships calibrated on the present climate). The second one is more difficult to overcome, and there is a real risk of confusion between historical data and model output, amplified by the fact that climate model outputs resemble actual climate data.

To illustrate this problem, consider the case of a water manager in Toulouse, in the Southwest of France. To know how to change his or her activities, he or she can ask climate modellers to provide model outputs for precipitation over this region up to 2100 and apply unchanged methodology with climate model outputs instead of climate data as inputs. But such a method could be dangerously misleading. Projections of future precipitation changes in Europe have been summarized by the Fourth Assessment Report of the IPCC (2007). From a climate scientist point of view, these results are very satisfying, as the patterns of change are very similar for all models, with an increase in precipitation in Northern Europe and a strong drying in the Mediterranean basin. But a water manager is much less satisfied as he/she realizes that, according to these models, precipitations in Toulouse could remain unchanged (according to the GISS model) or decrease by up to 30% (according to the CNRM model). How should she/he react to the possibility of the latter change, which would clearly require large modifications in water management strategies and infrastructures, and to this uncertainty? The traditional decision-making tools have not been developed to face such a situation and must, therefore, be amended.

A first conclusion is that, in this situation, climate modellers have to very careful when they are asked to provide model outputs. Not everybody is familiar with climate change modelling, and one could easily take model outputs as a reliable input for infrastructure design. To avoid such misunderstanding, a simple solution is to distribute climate model outputs to end-users only from a shared platform, where all climate model projections are available in a common format. Such a platform, already suggested by Milly et al. (2008), would be an equivalent of the IPCC Data Distribution Centre, but for high-resolution results. The creation of such a distribution infrastructure would limit the risk of misuse of climate model results.

3. New strategies to adapt to new climates

When a user is confronted with the multiplicity of model outputs, a natural reaction is to ask climate scientists to improve knowledge and understanding, and to provide, as soon as possible, reliable forecasts of future conditions. Of course, one can expect that climate science will progress in the future and that the range of climate projections will narrow, making their use easier.

There is increasing evidence, however, that improved knowledge does not mean narrower projection ranges. Indeed, even if models were perfectly accurate, uncertainty would not disappear. First, future levels of greenhouse gas emissions, which by nature cannot be forecasted, largely determine future climate change. But there are also large differences between the projections of different climate models that do not seem to be diminishing with time. The example of climate sensitivity, i.e. the increase in equilibrium global mean temperature when CO_2 concentration is doubled, is striking: the range of published estimates has remained essentially unchanged over three decades in spite of the improvement of climate models and our much better understanding of climate processes (see Roe and Baker, 2007; Ghil et al., 2008). As another example, new evidence that land-based glaciers (such as those in Greenland) may respond more quickly to warming and in less gradual and predictable ways has recently reduced the confidence in the IPCC's latest sea-level-rise projection range. So, climate models may well be unable to provide the information current decision-making frameworks need until it is too late to avoid large-scale retrofitting of infrastructure. Also, climate models are based on a set of common assumptions. The range of their results, therefore, underestimates the full range of uncertainty.

If climate models disagree, will climate observations tell us which one is right? Unfortunately, even though they will eventually, they will do it quite late in the century. For instance, changes in precipitation patterns in the Mediterranean basin may remain undetectable by statistical methods until 2050 (IPCC, 2007, Table 11.1). If we wait for climate change to be detectable and models to be fully validated, many investments designed before that time will be ill-adapted by the end of the century, with potentially large economic costs. Moreover, observations can be dangerously misleading: worst-case scenarios can arise from the difficulty in attributing observed changes to global climate change. For instance, multi-decadal variability can modify precipitation patterns over long periods. If these transitory modifications are understood by economic actors as anthropogenic climate change patterns, i.e. as permanent modifications, ill-designed adaptation strategies could be implemented and make the situation even worse than without adaptation.

Hurricanes are a good example of this situation, where observations cannot provide the required information: does the current high-activity level in the North Atlantic arise from climate change, as proposed by Emanuel (2005) and Webster et al. (2005), or does it arise from multi-decadal variability as proposed by Landsea (2005)? In the first case, hurricane activity is likely to keep increasing in the future and ambitious adaptation strategies must be implemented without delay to reduce vulnerability. But uncertainty concerning the driver of the current level of activity makes it difficult to make appropriate decisions regarding protection infrastructure and land-use restrictions (Hallegatte, 2006). Here, observations will not be able to provide the needed information for many decades, and waiting for this signal would be a critical error.

Since climate models and observations cannot provide what current decision-making frameworks need, the only solution is to amend these frameworks to make them able to take this uncertainty into account. To do so, infrastructure should be designed acknowledging (i) that it will need to cope with a larger range of climate conditions than before; and (ii) that this range is and will remain highly uncertain. In such a context, optimizing infrastructure design for a given climate may not be the best strategy. If it were possible to attribute probabilities to possible future changes, probabilistic optimization strategies could easily be introduced. But these probabilities are not available; even though some have been produced at the regional scale (e.g., Giorgi and Mearns, 2003), they are still heatedly debated.

A more suitable approach is to develop new strategies, especially those created to cope with the inherent uncertainties of climate change (e.g., Lempert and Schlesinger, 2000). For instance, it is possible to base decisions on scenario analysis (e.g., Schwartz, 1996) and to choose *the most robust solution*, i.e. the one that is the most insensitive to future climate conditions, instead of looking for the "best" choice under one scenario (Lempert et al., 2006; Lempert and Collins, 2007). More realistically, robustness can be included as an additional criterion in multi-criteria decision-making processes, or as an option value, i.e. a value of reversibility, in cost–benefit analyses with uncertainty (see below). In the public domain, the precautionary principle (Gollier and Treich, 2003) is another example of decision-making strategy that takes into account in an explicit manner the uncertainty (see an application to forestry in Spittlehouse and Stewart, 2003).

For professionals, these methods are consistent with those commonly used to manage exchange-rate risks, energy cost uncertainty, research and development outcomes, and many other situations that cannot be forecast with certainty. Such robust decision-making methods have already been applied in many long-term planning contexts, including water management in California (Groves and Lempert, 2007; Groves et al., 2007). For most decision-makers, the novelty will be the application of these methods to climate conditions. This requires users of climate information to collaborate more closely with climate scientists and to adapt their decision-making methods to the climate change context.

For climate scientists, the application of these techniques will require them to provide new information, more useful than bestguesses in these decision-making frameworks. In particular, they will be asked to provide the range of what is possible and of what is probable, and quantitative information about when observations will be able to discriminate between several scenarios. Specific investigations should be conducted to answer these questions. Examples of such investigations are (i) detection and attribution studies (e.g., Douville, 2006), to make the best use of all the available information and provide an estimate of how uncertainty will decrease in the future; (ii) identification, understanding and assessment of uncertainty sources in climate and impact models, to assess in a better way the possibility of unexpected climate outcomes; (iii) exploration of alternative scenarios and modelling approaches, to capture as much as possible the uncertainty on future climates.

4. Practical solutions to increase robustness

Within the new decision-making frameworks that aim at favouring robustness and including uncertainty information (e.g., Lempert's robust decision-making or precautionary principle), five

Table 2
Examples of adaptation options in various sectors, and their assessment in light of the strategies proposed by this article. In the "no regret strategy" column, "++" indicates options that yield benefits even with no climate change in most cases, while "+" indicates options that are no-regret only in some cases, depending on local characteristics. The last column provides a three-category ranking of the options that should be favoured, based on this analysis.

Sector	Examples of adaptation options	No regret strategy	Reversible / flexible	Existence of cheap safety margins	Soft strategy	Reduced decision horizon	Synergies with mitigation	Ranking
AGRICULTURE	• Developing crop insurance	+	+		+			1
	• Irrigation (possibly with water storage & transport)	+	–	+				2
	• Forestry with shorter rotation time	–	–			+		2
	• Development of resistant crops	++						1
COASTAL ZONES	• Coastal defences / sea walls	+	–	+				2
	• "Easy-to-retrofit" defences		+	+		+		1
	• Enhanced drainage systems	+	–	+				2
	• Restrictive land use planning	+	+	+				1
	• Insurance, warning and evacuation schemes	++	+		+			1
	• Relocation and retreat	–	–					3
	• Creation of risk analysis institution and long-term plans	+	+		+			1
HEALTH & HOUSING	• Air conditioning						–	3
	• Improved building standards	+		+			+	1
	• R&D on vector control, vaccines	+						1
	• Improvements in public health systems	++						1
WATER RESOURCES	• Institutionalization of long-term prospective	++	+		+			1
	• Loss reduction (leakage control, etc.)	++						1
	• Demand control and water reuse	++	+		+			1
	• Storage capacity increase (new reservoirs)	+	–	+				2
	• Desalination and water transport	+	–	+			–	3
HUMAN SETTLEMENTS	• Climate proofing of new building and infrastructure	+		+			+	1
	• Climate proofing of old building and infrastructure		–				+	2
	• Improvement of urban infrastructures	+	–	+			+	2
	• Restrictive land use planning	++	+	+				1
	• Flood barriers, storm / flood proof infrastructure	+	–	+				2
	• Development of early warning systems	++	+		+			1

examples of practical strategies can be proposed. These strategies are often found particularly desirable when using these frameworks. Table 2 lists several adaptation options in different sectors, and indicates if these options fall into one of the large categories of strategies that are described hereafter. This table is an illustration, but it also aims at indicating which adaptation options are most able to cope with the high level of uncertainty that climate change is creating.

4.1. No-regret strategies

"no-regret" measures constitute a first category of strategies that are able to cope with climate uncertainty. These strategies yield benefits even in absence of climate change. Table 2 indicates in the first column if each adaptation option is a "no-regret" strategy in all situations ("++"), in some situations only ("+"), or if the strategy would entail significant losses in the current climate ("−"). For example, controlling leakages in water pipes is almost always considered a very good investment from a cost–benefit analysis point-of-view, even in absence of climate change, and is identified with "++". On the other hand, additional irrigation infrastructure is an interesting measure in some regions in the current climate. In others, considering the high investment costs that are needed, it would be beneficial only if climate change decreases precipitations. So, irrigation is a no-regret strategy only in some regions, and is identified with "+".

Improving building insulation norms and climate-proofing new buildings is another typical example of no-regret strategy, since this action increases climate robustness while energy savings can often pay back the additional cost in only a few years. Considering its large-cost, on the other hand, it is unlikely that the climate proofing of existing buildings is no-regret. Land-use policies that aim at limiting urbanisation and development in certain flood-prone areas (e.g., coastal zones in Louisiana or Florida) would reduce disaster losses in the present climate, and climate change may only make them more desirable. Also, in many locations, especially coastal cities, building sea walls would be economically justified by storm surge risks with the current sea level (see Nicholls et al., 2007), and sea level rise will only make these walls more socially beneficial.

It would be interesting to know why these no-regret actions are not implemented yet. Many obstacles explain the current situation, including (i) financial and technology constraints, especially in poor countries; (ii) lack of information and transaction costs at the micro-level; and (iii) institutional and legal constraints. While the first two issues are well identified, more research is needed to understand the latter. For instance, what explains the difference in risk management between the Netherlands, where flood risks are seriously investigated and managed, and Louisiana, where flood defences have been neglected for decades? Detailed case studies should be able to answer such question and propose "best practices" that could be generalized. In many locations, the implementation of these practices would constitute a very efficient first step in a long-term adaptation strategy.

4.2. Reversible strategies

Second, it is wise to favour strategies that are reversible and flexible over irreversible choices. The aim is to keep as low as possible the cost of being wrong about future climate change. Examples of such measures are identified by a '+' symbol in the second column of Table 2. Among these examples, one can mention "easy-to-retrofit" defences, i.e. defences initially designed to allow for cheap upgrades if sea level rise makes them insufficient; the climate proofing of new buildings and infrastructures, which has an immediate cost but can be stopped instantaneously if new information shows that this measure is finally unnecessary; and insurance and early warning systems that can be adjusted every year in response to the arrival of new information. Another example is restrictive urban planning. When deciding whether to allow the urbanisation of an area potentially at risk of flooding if climate change increases river runoff, the decision-maker must be aware of the fact that one answer is reversible while the other is not. Refusing to urbanise, indeed, has a well-known short-term cost, but if new information shows in the future that the area is safe, urbanisation can be allowed virtually overnight. This option, therefore, is highly reversible, even though it is not costless since it may prevent profitable investments from being realized. Allowing urbanisation now, on the other hand, yields short-term benefits, but if the area is found dangerous in the future, the choice will be between retreat and protection. But retreat is very difficult politically, especially if urbanisation has been explicitly allowed. Protection is also expensive, and it is important to consider the residual risk: protection is efficient up to the protection design. If the protection is overtopped or fails, like in New Orleans, human and economic losses can be very large (Hallegatte, 2006; Nicholls et al., 2007). So, allowing urbanisation is very difficult to reverse, and this strategy is highly vulnerable to the underestimation of future risks. Of course, it does not mean that urbanisation should always be rejected. It only means that, in the decision-making process, the value of the reversibility of a strategy, often referred to as the "option value", should be taken into account.

The option value is often used to assess the possibility of delaying a decision (e.g., Ha-Duong, 1998), like in this urbanisation example. For many infrastructure decisions, however, waiting is not an option, since all climate-sensitive decisions (e.g., in water management or housing) cannot simply be delayed by decades. The valuation of reversibility, through the option value concept or through multi-criteria decision-making frameworks, have thus to be applied to the comparison of adaptation strategies with different "irreversibility levels".

4.3. Safety margin strategies

Third, there are "safety margin" strategies that reduce vulnerability at null or low costs. The existence of such strategies to manage sea level rise or water investments has been mentioned by Nicholls and Leatherman (1996), Groves and Lempert (2007) and Groves et al. (2007). And there are today practical applications already. For instance, to calibrate drainage infrastructure, water managers in Copenhagen now use run-off figures that are 70% larger than their current level. Some of this increase is meant to deal with population growth and the rest is to cope with climate change, which may lead to an increase in heavy precipitation over Denmark. This 70% increase has not been precisely calibrated, because such a calibration is made impossible by climate change uncertainty. But this increase is thought to be large enough to cope with almost any possible climate change during this century, considering the information provided by all climate models. This move is justified by the fact that, in the design phase, it is inexpensive to implement a drainage system able to cope with increased precipitation. On the other hand, modifying the system after it has been built is difficult and expensive. It is wise, therefore, to be over-pessimistic in the design phase. The same is often true for dikes and sea walls: construction costs alone are often manageable (see, e.g., The Foresight report on Flood and Coastal Defences, Volume 2, Table 5.2, available on http://www.foresight.gov.uk), a significant fraction of the total social cost of a dike arising from amenity costs (e.g., loss of sea view) and other indirect effects (e.g., loss of biodiversity, other environmental costs on ecosystems, or enhanced erosion in neighbouring locations). As a consequence, the marginal cost to build a higher dam is small compared to its total cost. If a dike has to be built today to cope with current storm surge risks, therefore, it may be justified to build it higher, in such a way that it can cope with future sea levels.

Often, when it is cheap, it is sensible to add "security margins" to design criteria, in order to improve the resilience of infrastructure to future (expected or unexpected) changes. As shown in the third column of Table 2, cheap safety margins can be introduced in many existing adaptation options, to take into account climate uncertainty: developing drainage infrastructures in developing-country cities can be considered as an adaptation measure; making these drainage infrastructures able to cope with more water than we currently expect is a "safety margin" strategy that makes this adaptation measure more robust.

The existence of cheap safety margins is especially important for adaptation measures that are not reversible or flexible. In Table 2, the options that are irreversible (e.g., retreat from coastal areas) and in which no cheap safety margins are available are particularly inadequate in the current context. The options that are irreversible but in which safety margins can be introduced (e.g., coastal defences or improvement of urban water management infrastructures) can be implemented, but only with a careful taking into account of future climate change scenarios.

4.4. Soft strategies

Fourth, technical solutions are not the only way of adapting to changing climates. Sometimes, institutional or financial tools can also be efficient. Examples of such solutions are identified in the fourth column of Table 2. For instance, the "institutionalization" of a long-term planning horizon may help anticipate problems and implement adequate responses: in the framework of the California Water Plan, all water suppliers that provide water to more than 3000 customers in California have to carry out, every 5 years, a 25-year prospective of their activity, including the anticipation of future water demand, future water supply sources, and "worst-case" drought scenarios. These kinds of exercise are very useful because they force planners to think several decades ahead, they create contacts between economic agents and climate scientists, and they help shape strategies to cope with future changes. In the present situation, where parameters that used to be known become uncertain, a long-term planning horizon is key to determine where and how to change business practices.

Institutional solutions have also an important role to play in coastal zone management: while managing coastal floods did not require regular updates in a world with an almost constant sea level, climate change and sea level rise will make it necessary to analyse coastal flood risks on a regular basis and to implement upgrades when required. The creation of specific institutions to carry out these analyses may, therefore, be an efficient adaptation option.

As another example, agriculture is very sensitive to water availability. But, where annual precipitations will decrease, problems in the agriculture sector may come first from extreme events in water scarcity (e.g., long droughts) rather than from the decrease in average water availability. In the Mediterranean region, for example, average yields are expected to decrease, but most of the concern is about the recurrence of extreme droughts with disastrous consequences. Where problems arise from extremes, there are several ways of adapting to less water. The aim is to transform the uncertain annual loss – potentially large and disastrous – into a certain and manageable loss. To do so, in particular, technical and financial solutions coexist. First, technical solutions can be implemented, using water management infrastructure, from water reservoirs to water transport. These adaptation strategies, however, are highly dependent on future precipitation levels. Some of them, like water reservoirs, will be efficient if climate change remains moderate, but cannot cope with the most pessimistic projections. Facing a reduction in water availability, is it safe to invest substantially in adaptation projects that may become inefficient if the situation worsens?

In these cases, other adaptation strategies can be explored, like insurance schemes (see, e.g., Linnerooth-Bayer et al., 2003; Hellmuth et al., 2007). If the problem for farmers is to deal with the worst years, an insurance scheme that protects them against heavy losses when weather is unfavourable may be as efficient as "hard" adaptation options involving costly infrastructure.

In the same way, in hurricane-prone regions, it may be more efficient to implement an efficient warning and evacuation system combined with strong (possibly expensive) insurance scheme and recovery plan than to protect all populations with seawalls and dikes. In the former case, the population is evacuated in dangerous conditions (e.g., an approaching hurricane) to avoid deaths and casualties, and material losses are paid by insurance claims, so that recovery and reconstruction are as effective as possible. The insurance premium the population will have to pay to live in this at-risk area may be large, but remain lower than the cost of protecting the areas with dikes. Of course, warning systems are not flawless and it is always difficult to decide whether and when to evacuate, but the Katrina experience demonstrated that hard protection can also fail, with the most tragic consequences.

As shown in Table 2, soft adaptation options are also reversible solutions. The key advantage of "soft" adaptation options, indeed, is that they imply much less inertia and irreversibility than hard adaptation: an insurance scheme can be adjusted every year, unlike a water reservoir. The risk of "sunk costs" if climate projections are wrong is much lower for institutional and financial strategies than for technical adaptation projects, which makes them more suitable to the current context of high uncertainty.

Soft options like land-use plans, insurance schemes or early warning systems will have an influence on business investment choices and household decisions and, therefore, on "hard" investments. For instance, land-use planning restrictions can be seen as soft options, but their consequences in terms of construction make such a qualification questionable. As a consequence, no option is purely a "soft" option. In Table 2, only soft options with limited hard consequences, like early-warning schemes or insurance, have been flagged as "soft strategies".

4.5. Strategies that reduce decision-making time horizons

Fifth, the uncertainty regarding future climate conditions increases rapidly with time. Reducing the lifetime of investments, therefore, is an option to reduce uncertainty and corresponding costs. This strategy has already been implemented in the forestry sector by choosing species that have a shorter rotation time. Since species choice cannot be made reversible and no safety margins are available in this sector, this option is interesting in spite of its cost. In other sectors, it is also often possible to avoid long-term commitment and choose shorter-lived decisions. For example, if houses will be built in an area that may become at risk of flooding if precipitation increases, it may be rational to build cheaper houses with a shorter lifetime instead of high-quality houses meant to last 100 years.

4.6. Taking into account conflicts and synergies between strategies

A last point deserves to be mentioned. Adaptation strategies often have side-effects that can be either negative or positive. For instance, in the case of coastal infrastructure to protect against storm surge such as sea walls, these may threaten the tourism industry because they change landscape, ecosystem health and beach leisure attractions. Coastal attractiveness for leisure and tourism activities is closely linked to various parameters such as landscapes (Lothian, 2006), the quality of the environment, water availability, etc. As a consequence, in some contexts, hard protection would simply not be an option. Equally important, hard protection could contribute to fish stocks depletion by further damaging coastal ecosystems (Clark, 1996). Since 90% of fishes depend on coastal zones at one point in their life cycle (Scialabba, 1998), such impacts could have a significant impact on economic income from fisheries. Taking into account environmental costs on ecosystems is thus essential.

There are also conflicts between adaptation options. For instance, an increased use of snow-making to compensate for shorter skiing seasons in mountain areas would have negative consequences for water availability and, e.g., agriculture. This example shows that adaptation strategies that look profitable when considering only one sector may be sub-optimal at the macroeconomic scale because of negative externalities. As a consequence, public authorities will have to be aware of this risk and monitor the emergence of new externalities from adaptation behaviours.

Adaptation also interacts with mitigation policies. For example, improved building norms would lead to large ancillary benefits in terms of energy consumption and reduced greenhouse gas emissions. And indeed, the benefits in terms of emission reduction of several options of Table 2 (identified with a "+" in the last column) make these measures interesting, even when they imply some irreversibility. But conflicts may also appear between adaptation and mitigation measures. Many adaptation strategies that are appealing today imply increased energy consumption (identified with a "−" in the last column of Table 2). In the design of adaptation strategies, therefore, future energy costs have to be taken into account: if there is a high carbon price in 2030, desalinisation plants using fossil fuels may become excessively expensive to run. Considering the huge investment cost of these plants, this possibility has to be accounted for in the decision-making process. Moreover, there is an unfortunate correlation between energy costs and climate change impacts. If climate change and its impacts appear to be worse than expected in 50 years, stricter mitigation strategies are likely to be introduced, making energy costs and carbon price rise. Highly energy-consuming adaptation options, therefore, seem to be particularly non-robust to unexpected climate evolutions.

More broadly, there is a particularly complex relationship between adaptation and mitigation policies. First, mitigation efforts will influence the amplitude and pace of climate change, modifying adaptation needs. Second, adaptation capacity, limits and costs make it more or less acceptable to exceed certain GHG concentration thresholds and are, therefore, important inputs in the choice of long-term climate policy targets. Third, stabilisation targets that have been proposed so far (e.g., the 2 °C target of the European Union) imply a significant replacement of infrastructures in the following decades. This replacement provides a unique window of opportunity to increase the economic robustness to future climate change if adaptation considerations are taken into account. And finally, the carbon price, created by mitigation policies, will make some adaptation strategies more or less cost-effective. All these links (see a more detailed analysis in Lecocq and Shalizi, 2007) call for an integrated design and assessment of adaptation and mitigation policies, which are often developed by distinct communities. Integrated assessment, as a discipline, should be an answer to this challenge. As shown in Carter et al. (2007), significant progresses are being made toward the development of (i) integrated assessment models, able to simulate the consequences of policies and measures including a large range of constraints and objectives (e.g., economic, environmental, social, political), and of (ii) methodologies to design and assess policies and measures in an open and interdisciplinary framework, able to include insight and knowledge from experts, stakeholders, and from the population.

The empirical analysis proposed in this article and in Table 2 is not sufficient to make specific adaptation decisions, since all adaptation decisions will have to be site-specific. But this analysis suggests strategies that should be considered in priority, because they can be implemented without waiting for more information on future climate change. Table 2 provides in the last column a three-category ranking of these options. The options are ranked first and coloured in green when they are evaluated positively in light of the present analysis. Other options, ranked second and coloured in yellow, have to be considered in spite of their lack of flexibility because this drawback is compensated either by the fact that they yield benefits in the current climate, by the availability of cheap safety margins, by the reduction of decision horizons, or by side-benefits in terms of greenhouse gas emissions. The other options, ranked third, may also be beneficial in spite of the climate uncertainty, but their short-term cost, the irreversibility they imply, or their consequences in terms of GHG emissions make them less adequate in the present situation of climate uncertainty. Climate change, however, may eventually make these last strategies necessary in spite of their weaknesses. If this is the case, their implementation would require more information on climate change and, therefore, a delay in application to wait for this information to become available.

5. Conclusion

Over the next few decades, the main change global warming will bring us may not be the change in climate itself. It may be the uncertainty regarding future climate conditions, which was marginal during previous centuries and, therefore, was often neglected in decision-making. Now, uncertainty in future climate change is so large that it makes many traditional approaches to designing infrastructure and other long-lived investments inadequate.

This paper makes the case that end-users should not expect climate scientists to solve this problem by providing certain and accurate climate forecasts in due time. Fundamental scientific uncertainty will prevent climate models from providing this information soon. Natural variability that makes it difficult to detect and attribute climate changes will also prevent observations from doing so.

End-users, therefore, have to change the way they make decisions, to introduce climate uncertainty in their everyday operations. In most cases, they know how to do so, since uncertainty is already at the heart of many economic decisions: energy prices, exchange rates, and future technological developments are volatile and uncertain, and cannot be forecasted with precision. In this (already long) list of uncertain factors, it is urgent to include future climate conditions, to make sure that all the information climate scientists can produce is used in the most adequate way. If uncertainty is taken into account in all long-term decisions, many infrastructure projects will be better adapted in the future, and climate change impacts will remain lower and more manageable (Hallegatte, 2007). Only such an anticipatory adaptation strategy can buy us the time we need to wait for (still-to-be-implemented) mitigation policies to become effective.

Acknowledgments

The author wishes to thank Shardul Agrawala, Raphaël Billé, Christian De Perthuis, Suraje Dessai, Patrice Dumas, Hans-Martin Füssel, David Groves, Robert W. Hahn, Franck Lecocq, Mike Mastrandrea, Simon Dietz, and two anonymous referees for their useful comments and suggestions on an earlier version of this article. All remaining errors are the author's.

References

Adger, W.N., Agrawala, S., Mirza, M.M.Q., Conde, C., O'Brien, K., Pulhin J., Pulwarty, R., Smit, B., Takahashi, K., 2007. Assessment of adaptation practices, options, constraints and capacity. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson (Eds.), Climate Change 2007: 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, UK, pp. 717–743.

Carter, T.R., Jones, R.N., Lu, X., Bhadwal, S., Conde, C., Mearns, L.O., O'Neill, B.C., Rounsevell, M.D.A., Zurek, M.B., 2007. New assessment methods and the characterisation of future conditions. In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden, C.E. Hanson (Eds.), Climate Change 2007: 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, UK, pp. 133–171.

Clark, J.R., 1996. Coastal Zone Management Handbook. Lewis Publishers, 694 pp.

Douville, H., 2006. Detection–attribution of global warming at the regional scale: how to deal with precipitation variability? Geophysical Research Letters 33, L02701.

Emanuel, K., 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature 436, 686–688.

Fankhauser, S., Smith, J.B., Tol, R.S.J., 1999. Weathering climate change: some simple rules to guide adaptation decisions. Ecological Economics 30 (1), 67–78.

Ghil, M., Chekroun, M.D., Simonnet, E., 2008. Climate dynamics and fluid mechanics: natural variability and related uncertainties, Physica D, Invited survey paper for Special Issue on The Euler Equations: 250 Years On., Physica D, 237, 2111–2126, doi:10.1016/j.physd.2008.03.036.

Giorgi, F., Mearns, L.O., 2003. Probability of regional climate change based on the reliability ensemble averaging (REA) method. Geophysical Research Letters 30 (12), 1629–1632, doi:10.1029/2003GL017130, 2003.

Gollier, C., Treich, N., 2003. Decision-making under scientific uncertainty: the economics of the precautionary principle. Journal of Risk and Uncertainty 27 (1), 77–103.

Groves, D.G., Lempert, R.J., 2007. A new analytic method for finding policy-relevant scenarios. Global Environmental Change 17, 73–85.

Groves, D.G., Knopman, D., Lempert, R., Berry, S., Wainfan, L., 2007.In: Presenting Uncertainty About Climate Change to Water Resource Managers—Summary of Workshops with the Inland Empire Utilities Agency, RAND, Santa Monica, CA.

Ha-Duong, M., 1998. Quasi-option value and climate policy choices. Energy Economics 20, 599–620.

Hallegatte, S., 2006. A cost–benefit analysis of the New Orleans Flood Protection System, Regulatory Analysis 06-02. AEI-Brookings Joint Center. March 2006.

Hallegatte, S., 2007. Do current assessments underestimate future damages from climate change? World Economics 8 (3), 131–146.

Hallegatte, S., Hourcade, J.-C., Ambrosi, P., 2007. Using climate analogues for assessing climate change economic impacts in urban areas. Climatic Change 82 (1–2 (May)), pp. 47–60, doi:10.1007/s10584-006-9161-z.

Hellmuth, M.E., Moorhead, A., Thomson, M.C., Williams, J. (Eds.), 2007. Climate Risk Management in Africa: Learning from Practice. International Research Institute for Climate and Society (IRI), Columbia University, New York, USA.

IPCC, 2007. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), 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, United Kingdom and New York, NY, USA, 996 pp.

Landsea, C.W., 2005. Meteorology: hurricanes and global warming. Nature 438, E11–E13.

Lecocq, F., Shalizi, Z., 2007. Balancing expenditures on mitigation and adaptation to climate change: an exploration of issues relevant to developing countries. Policy Research Working Paper 4299. The World Bank.

Lempert, R.J., Schlesinger, M.E., 2000. Robust strategies for abating climate change. Climatic Change 45 (3/4), 387–401.

Lempert, R.J., Groves, D.G., Popper, S.W., Bankes, S.C., 2006. A general, analytic method for generating robust strategies and narrative scenarios. Management Science 52 (4), 514–528.

Lempert, R.J., Collins, M.T., 2007. Managing the risk of uncertain thresholds responses: comparison of robust, optimum, and precautionary approaches. Risk Analysis 27, 1009–1026.

Linnerooth-Bayer, J., Mace, M.J., Verheyen, R., 2003. Insurance-related actions and risk assessment in the context of the UNFCCC. In: Background Paper for UNFCCC Workshop on Insurance and Risk Assessment in the Context of Climate Change and Extreme Weather Events. 12–13 May 2003, Bonn, Germany.

Lothian, A., 2006. Coastal landscape assessment. In: Coast to Coast Conference, Melbourne, 23 May.

Milly, P.C.D., Betancourt, J., Falkenmark, M., Hirsch, R.M., Kundzewicz, Z.W., Lettenmaier, D.P., Stouffer, R.J., 2008. Climate change: stationarity is dead: whither water management? Science 319 (5863), 573, doi:10.1126/science.1151915.

Nicholls, R., Leatherman, S., 1996. Adapting to sea-level rise: relative sea-level trends to 2100 for the United States. Coastal Management 24 (4), 301–324.

Nicholls, R.J., S. Hanson, C. Herweijer, N. Patmore, S. Hallegatte, J. Corfee-Morlot, J. Chateau, R. Muir-Wood, 2007. Screening Study: Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes, OECD Working Paper, available on http://www.oecd.org/document/56/0,3343,en_2649_201185_39718712_1_1_1_1,00.html.

Roaf, S., Crichton, D., Nicol, F., 2005. Adapting Buildings and Cities for Climate Change. Architectural Press, Elsevier.

Roe, G.H., Baker, M.B., 2007. Why is climate sensitivity so unpredictable? Science 318, 629–632.

Scialabba, N., 1998. Integrated Coastal Management and Agriculture, Forestry and Fisheries. FAO Guidelines. Environment and Natural Resources Service, FAO, Rome.

Schwartz, P., 1996. The Art of the Long View. Double Day, New York.

Spittlehouse, D.L., Stewart, R.B., 2003. Adaptation to climate change in forest management. BC Journal of Ecosystems and Management 4 (1), 1–11.

Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.-R., 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science 309, 1844–1846.

Yohe, G., Andronova, N., Schlesinger, M., 2004. Climate: to hedge or not against an uncertain climate future? Science 306, 416–417.