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Designing Climate Change Adaptation Policies

An Economic Framework

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Abstract

Adaptation has long been neglected in the debate and policies surrounding climate change. However, increasing awareness of climate change has led many stakeholders to look for the best way to limit its consequences and has resulted in a large number of initiatives related to adaptation, particularly at the local level. This report proposes a general economic framework to help stakeholders in the public sector to develop effective adaptation strategies. To do so, it lays out the general issues involved in adaptation, including the role of uncertainty and inertia, and the need to consider structural changes in addition to marginal adjustments. Then, it identifies the reasons for legitimate public action in terms of adaptation, and four main domains of action: the production and dissemination of information on climate change and its impacts; the adaptation of standards, regulations and fiscal policies; the required changes in institutions; and direct adaptation actions of governments and local communities in terms of public infrastructure, public buildings and ecosystems. Finally, the report suggests a method to build public adaptation plans and to assess the desirability of possible policies.

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Designing Climate Change Adaptation Policies: An Economic Framework

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Introduction

To limit the negative consequences of climate change on societies, we can either reduce greenhouse gas emissions (**mitigation**), or adapt to the effects of climate changes (**adaptation**). However, these two options have not been given equal consideration, and **adaptation has long been neglected in the climate change** debate. This imbalance is indicative of the real difficulties inherent in adaptation, like the treatment of uncertainty on the future impacts of climate change or a certain number of other methodological problems that will be dealt with in this report. It is also the result of the deliberate intention to avoid the discussion on adaptation, which is perceived by some stakeholders as a less valid solution because it focuses on the consequences of climate change and not on its causes, and even as a dangerous solution since it could stand in the way of the discussion on mitigation.

The situation has considerably changed since the mid-2000s. The massive dissemination of information on climate change has led **many stakeholders in the public and private sectors, particularly at the local level, to take an interest in the impacts of climate change and to ask themselves what they can do to limit the consequences** (1). Awareness of the fact that the climate is going to change whether or not mitigation policies at the international level are successful makes the issue of adaptation that much more urgent (2).

For the decision-maker, **"adaptation to climate change" is nevertheless very far from being an operational concept.** Adaptation encompasses extremely varied types of actions (direct protection of people and assets, actions to support this protection, reactions with respect to impacts, etc.), which can be applied to a wide range of sectors (agriculture, water, energy, transportation, etc.) with very different problems depending on geographic scales and zones (coasts, mountains, urban areas, etc.) and using widely diversified instruments (standards, information, tax measures, transfers, investment choices in infrastructure, etc.) (IPCC, 2007).

The aim of this report is to provide an overall economic framework that will help decision-makers in the public and private sectors to establish effective adaptation strategies. It is assumed in this report, with the exception of particular situations, that adaptation actions raise similar questions and present common characteristics that lead to recommendations applicable to a wide range of situations. It is obvious that this report does not intend to replace detailed economic analyses of each specific adaptation problem. For example, it does not examine financing sources for adaptation measures and only identifies the distribution problems that could arise from this financing. In contrast, it provides the methodological bases for the preparation of detailed analyses of adaptation problems.

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[1] Since the middle of the years 2000, we have observed a large number of initiatives related to adaptation to climate change, at the level of local government (many communities have adopted climate change plans that include both mitigation and adaptation), business (i.e., in the engineering and energy sectors), and the professional sectors (i.e., insurance and forestry).

[2] Even if greenhouse gas (GHG) emissions were completely stopped today, the climate will nevertheless continue to change because of the inertia of the climate system. If GHG emissions continue, it is likely that the climate will undergo additional changes whose amplitude will, on the other hand, depend on the level of emissions and, therefore, on the success or failure of international mitigation policies.

The report is divided into five sections. The first three sections deal with the different aspects of the problem raised by adaptation in terms of public policy-making, and the following two, of a more methodological nature, address the issue of economic assessment of adaptation measures and the construction of a national strategy.

Section 1 establishes the methodological framework of the report by defining adaptation and by describing its main characteristics.

Section 2 is devoted to the role and types of public action in a world where the benefits of adaptation actions are mainly private, and where, as a result, the legitimacy of public intervention is not always obvious. Public intervention can even have perverse effects if it incites agents to adopt more risky behaviors (what economists refer to as "moral hazard"). This section lays out the circumstances in which public intervention in relation to adaptation is desirable or necessary and takes a look the different instruments that public authorities may use for this purpose. Finally, it gives some examples of applications for the different sectors.

Section 3 is devoted to the spatial and territorial aspect of adaptation whose implementation cannot be the result of the simple juxtaposition of sectorial measures alone. This section deals with the long-term impact of climate change on the spatial distribution of activities and people, which has large indirect global impacts through changes in the functioning of markets and migratory flows. Consequently, the section addresses adaptation issues at the international level and the questions that they raise, particularly that of the "additionality" of resources devoted to adaptation.

Section 4 proposes a method for building an adaptation strategy at the national level in the absence of a unique metrics to compare the performance of different solutions. This seven-stage process begins with the broad identification of a set of possible adaptation measures that is then reduced by identifying the most urgent measures – those resulting from imminent impacts or concerning choices to be made today but that will have very long-term consequences.

Finally, Section 5 examines the different possible approaches for economically assessing adaptation measures within a framework of uncertainty on the future impact of climate change. It particularly shows how cost-benefit analysis (private or public) can be used to size each measure and to facilitate the allocation of resources between competing measures.

The first version of this report was drawn up at the request of the Economic Council on Sustainable Development (CEDD) of the French Ministry of Ecology, Energy, Sustainable Development and the Sea [3]**,** within the national consultation to design an integrated national adaptation plan that should be published in 2011. The economic framework proposed by the report appears however to be sufficiently generic to be of interest to government agencies and private experts worldwide. It is for this reason that we have provided an English version. With respect to the initial version, the content is comparable, but examples and illustrations have been modified to provide a more global point of view.

[3] The first version of the report, in French, can be found at http://developpement-durable.gouv.fr/IMG/pdf/001-3.pdf.

1. What does adaptation to climate change mean?

This section proposes a general definition of adaptation (1.1). It then focuses on four characteristics that determine its implementation (1.2) and gives a few orders of magnitude of the costs of adaptation (1.3).

1.1. A general definition of adaptation

We can define adaptation to climate change as "**the set of organization, localization and technical changes that societies will have to implement to limit the negative effects of climate change and to maximize the beneficial ones**" [(4)]. Possible adaptation actions include, for example, removing populations and assets from areas at risk of flooding as a result of climate change, adopting crop varieties that are more resistant and better adapted to future climates, or adjusting energy networks to expected variations in energy consumption.

According to Smit et al. (2000), two types of adaptation can be distinguished. **Reactive adaptation** consists of reacting *ex post* to adverse impacts of climate change when they occur. In contrast, **anticipatory adaptation** consists of taking action before impacts occur to reduce vulnerability to these impacts and to limit adverse consequences or to take advantage of them. For example, evacuating people from a flooded zone and relocating them in a safe zone is considered to be reactive adaption, whereas changing the land-use plan in anticipation of future flooding is considered to be anticipatory adaptation.

Even though it may be evident from an intuitive point of view, **the line between anticipatory adaptation and reactive adaptation is sometimes not that clear.** For example, the Climate Plan adopted in France after the 2003 heat wave can be interpreted as a reaction to the 2003 event, as well as a way to anticipate similar (climate-change related) events in the future.

The distinction between reactive adaptation and anticipatory adaptation is nevertheless very important in terms of public policies because the motivations for these two types of adaptation are different. Anticipatory adaption (like mitigation) uses resources that exist today to prevent possible crises in the future or to take advantage of climate changes. On the other hand, reactive adaptation uses resources to deal with events at the time they occur. Practically speaking, **political policy decisions are often easier to make after a crisis. However, the cost of preventive actions is often much lower than the cost of reactive actions** [(5)].

1.2. Uncertainty, dynamics, inertia and bifurcations: four major issues for adaptation strategies

One of the main difficulties for developing adaptation strategies is dealing with uncertainty. This uncertainty is the sum of three components:

- **Uncertainty about the global scenario of climate change.** The impacts of climate change and their associated risks are not comparable depending on whether we choose a scenario in which anthropogenic emissions of greenhouse gases and climate sensitivity

[4] Techniques aimed at artificially reducing climate change through an additional intervention on the climate ("geo-engineering") are not included within the scope of this report.

[5] For example, a warning system would have probably made it possible to considerably limit the loss of human lives linked to the 2004 tsunami in the Indian Ocean (Athukorala and Resosudarmo, 2005), but this type of system was only set up after the event. In the same way, in a comparative analysis, Hallegatte (2010) shows that the purely reactive risk management in New Orleans leads to increasingly serious and costly catastrophes, whereas proactive risk management in Holland has made it possible to manage risks for more than a half century.

lead to an average temperature increase of +2°C or one of +4°C. It would be dangerous to plan to only one of these two scenarios today. Taking the 2°C scenario, we run the risk of putting off taking the measures necessary to deal with the impacts of a 4°C scenario until it is too late. Taking the 4°C scenario, we run the risk of overinvesting in adaptation actions and therefore wasting scarce resources.

- **Uncertainty how global scenarios will translate at the local level.** For example, even for a given amount of global warming (measured as a change in global mean temperature), climate models diverge on the way in which climate change will affect the frequency and intensity of storm events in the north of Europe. Similarly, half of the climate models project an increase in precipitation in West Africa; the other half projects the opposite. Uncertainty is therefore exacerbated when we have to assess the local impacts of climate change to establish an adaptation strategy. Moreover, local climate changes are obscured by natural variability, making it particularly difficult to detect them.
- **Uncertainty about the reaction of major cycles (e.g., water), ecosystems and societies to global and local climate changes.** The response of ecosystems and human communities to changes in local climates is also extremely uncertain, but it influences what is an effective adaptation strategy. For example, the ability of coral reefs to cope with sea water warming, seal level rise and ocean acidification is highly uncertainty, but relevant adaptation options for small islands depend strongly on this issue. Adaptation strategy design needs to include this uncertainty from the earliest stages.

As we will see below, the most effective method for taking this uncertainly into account is to ensure that economic stakeholders have the best information possible on the impacts of climate change and to encourage approaches that maintain flexibility for future action as additional information becomes available.

A second specificity of adaptation is its dynamic character. Adaptation is not a specific action, aimed at going from a stable situation to a new one that is different but stable as well. On the contrary, societies will have to adjust to a climate that will change at a sustained rate for centuries to come [(6)]. **The challenge is therefore to know how and at what price we can adapt our life styles and our economic system to a "perpetually changing" climate.** To address this challenge, it is important to consider adaptation as a basically long-term transitory process. In other words, an adaptation plan for several years would only be part of a very long-term plan (see Section 4).

A third important characteristic to be considered is the inertia of our socio-economic systems. The uncertainty and the dynamic character of adaptation would be easier to take into account if it was possible to correct easily adaptation trajectories. However, many sectors have a high degree of inertia that forces us to make choices with long-term and even very long-term consequences. The time scales of several economic sectors like the forestry sector or those with heavy infrastructure (housing and urbanism, energy production, flood management, etc.) are therefore of the same order of magnitude than the time scale for climate change. Decisions concerning the localization of assets have particularly long time horizons that considerably exceed the lifespan of the installed capital. Moreover, it cannot be forgotten that inertia is not just technical, and institutional: regulatory and even cultural inertias must be taken into account. The socio-economic inertia that results from all of these mechanisms has three consequences:

- **Defining adaptation measures becomes more complex because it is necessary to take action very far ahead of time.** For example, a building built in 2000 with a lifespan of 150 years (typical for Paris) should be adapted to the current climate in Paris as well as the climate in 2160, which will probably be very different from the climate

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[6] Past greenhouse emissions are sufficient to increase sea levels over several millenniums.

today. However, it is more complicated to build a building (or any type of infrastructure) adapted to a wide range of climates rather than a specific, stable, well-known climate. We must therefore either build buildings adapted to a narrow climate range and that are therefore less costly, but whose operational lifespan may be reduced (for example, it could be necessary to tear down and rebuild the buildings in 2050, whereas they are still in good condition), or to take varied climates into consideration in the construction with a potentially longer operational lifespan, but at a much higher cost.

- **The combination of uncertainty on climate change and of the long asset lifespan leads to the risk of maladaptation** (see Box n°1). Maladaptation is not just related to the future climate. In fact, our societies are not necessarily adapted to today's climate. This current maladaptation is often referred to as an "adaptation deficit." For example, major investments have recently been made in many countries in areas that are flood-prone even in the absence of climate change. Climate change adaptation must not necessarily aim at maintaining the current risk level that we may consider to be too high. When the current situation can be qualified as sub-optimal, an adaptation plan may include measures that would be desirable, even without climate change – often qualified as the "reduction of the current adaptation deficit" – as well as measures that can only be justified because there is a climate change – and that constitute adaptation in the strict sense of the word (this question is also addressed in Box n°4 on the definition of adaptation costs).
- **Adaptation and climate change time scales are too long for us to be able to learn much from experience or to learn by doing,** at least on the short-term [7].

A fourth difficulty for developing adaptation strategies is related to the fact that **in many cases, it is too costly or technically impossible to adapt "at the margin" while maintaining the same activities or services under a new climate. Adapting to climate change therefore may require "bifurcations" towards new activities and/or towards new locations.** For example, it is likely that low and medium-altitude winter sports resorts will no longer be able to provide ski activities at some point in the future and it might be underoptimal trying to preserve these activities at high cost (see Box n°2). To be able to foresee these types of bifurcations, adaptation policies must be developed within an intersectoral framework where overall land-use development is taken into consideration. Moreover, experience shows that such economic bifurcations often involve difficult problems, in particular in terms of employment, and are difficult to trigger and drive.

1.3. Assessment of the global costs of adapting to climate change

The cost of adapting to climate change is the sum of investment costs and operating costs linked to the establishment of adaptation strategies. It is important to note that adaptation will not be able to completely expunge the impacts of climate change. Consequently, the global cost of climate change will be the result of adaptation costs plus the cost of residual impacts after adaptation measures are put in place. The aim of a successful adaptation strategy is therefore to find a satisfactory time and space distribution of adaptation expenses that minimizes this global cost over time.

[7] In contrast, we can use "climatic analogs" to help us reason intelligently. Within this context, development experiences in sub-tropical and tropical countries are particularly interesting for countries with temperate climates.

Box n°1: The concept of "maladaptation"

Measures designed to adapt to the effects of climate change can lead to results that are not consistent with expectations, and "maladaptation risks" should not be underestimated. Maladaptation is defined by the IPCC (the Intergovernmental Panel on Climate Change) as "a change in natural or human systems that leads to an increase rather than a decrease in vulnerability."

A maladaptation situation may arise, for example, after a calibration error, i.e., a poor calibration of adaptation measures following an inaccurate prognosis of the nature or extent of future changes or an inadequate response to this prognosis. It may also occur when an adaptation measure leads to the transfer of the vulnerability of one system to another, or one period to another (a measure may be positive for one period and then negative for another, or vice versa).

A distinction must be made between two sources of maladaptation. First, a maladaptation situation *ex post* can result in entirely appropriate decisions based on information available *ex ante*. As a result of the uncertainty of the impacts of climate change, the analysis *ex ante* often only makes it possible to limit the range of adaptation choices possible without limiting it to a specific choice. The choice of the measure to be taken among the set of measures compatible with the information available *ex ante* on climate change will then be a sort of wager on the part of society (see Section 5). For example, it may appear desirable today to better regulate new construction in low coastal zones. However, if we realize in 2050 that the most optimistic scenario on the rise in sea levels was the right one, this adaptation measure could then appear to be inadequate, even if it is (and remains) desirable today. This type of maladaptation cannot be avoided and can only be regretted *ex post* if all of the information available was not used *ex ante*.

On the other hand, a maladaptation situation can also arise from a "poor choice" *ex ante*, i.e., inadequate consideration of the information available. This is the case, for example, if adaptation measures are established in view of a unique climate scenario, without including uncertainty, or even if advanced signs of local climate change were not detected early enough by stakeholders. This type of maladaptation can lead to regrets *ex post* since all of the information available was not used to its best advantage *ex ante*. This type of situation could be avoided if the methodologies for the development of adaptation strategies are well designed and satisfactorily implemented.

Reducing the risk of maladaptation is possible, in particular, by giving priority (i) to "no-risk" strategies that reduce the vulnerability of climate change while both reaping immediate co-benefits and maintaining a degree of efficiency independently of which climate change scenario reveals correct; or (ii) to "flexible" or "reversible" strategies that can be easily modified as new information becomes available.

Several studies (see Agrawala and Fankhauser, 2008, for a review) **attempt to assess the cost of adaptation measures**, particularly in the infrastructure sector. They are based on two distinct methodologies: (1) "top-down" approaches, based on sums invested every year in sectors sensitive to climate conditions, and that assume that climate change will lead to additional costs (on the order of 10%) on these investments, and (2) "bottom-up" approaches that attempt to identify and assess the investments necessary in each of the sectors concerned (protection of coasts, water, agriculture, etc.).

"Top-down" estimates of the Word Bank (2006) and the United Nations Development Program (UNDP, 2007) assess adaptation costs at between 9 and 109 billon dollars per year for developing countries. The United Nations Framework Convention on Climate Change (UNFCCC, 2007) proposes an assessment of 49 to 171 billion dollars per year for all countries.

A more recent World Bank analysis (World Bank, 2009) concludes that the cost of developing countries to adapt to climate change between 2010 and 2050 can be estimated at US$70 billion to US$100 billion a year. These estimates must be taken with a great deal of precaution given the simplicity of the methods used, which emphasize investment costs but neglect operating costs, and because of the difficulty in accounting for the "adaptation deficit", i.e., the inadequate adaptation to the current climate conditions (see Parry et al., 2009).

"Bottom-up" estimates are based on different methodologies depending on the sector being considered and on hypotheses that are not necessarily consistent with each other. This makes it difficult to pool their results in order to calculate the cost of adaptation at the global or national level. We can nevertheless observe that this type of analysis generally assumes adaptation costs that are less than those of estimates of top-down studies.

We can also add that **these studies provide very little information about the distribution of these costs between public budgets, producers and consumers**, whereas the effectiveness of an adaptation strategy involves not only a realistic estimate of adaptation costs but of the capacity to distribute them among the different private and public stakeholders as well.

2. Role and types of public actions with respect to adaptation

This section examines the reasons that justify public intervention with respect to adaptation from a theoretical point of view (2.1), takes a look at the different types of instruments to be considered (2.2), and then gives some examples of applications for the major sectors concerned (2.3).

2.1. Justifying public intervention en terms of adaptation

As mentioned above, mitigation reduces risks linked to climate change, both known and unknown, and regardless of location. In economic terms, **mitigation produces what is known as a public good** [8]. Economic theory suggests that public goods are spontaneously produced in insufficient quantity, as it is in the interest of each economic actor to take advantage of a public good produced by others without having to make the effort himself. From the point of view of economic theory, public action is therefore legitimate (and necessary) to ensure that the public good be produced at the socially optimal level.

The case of adaptation is different. Adaptation only reduces certain risk categories, most often in very specific geographic zones. In economic terms, **adaptation generally produces what is referred to as private goods.** For example, reinforcing a building so that it will be able to withstand bigger storms is only of benefit to the inhabitants of this building. In certain cases, adaptation can also produce what is known as "club" goods or services, i.e., access to a seasonal forecasting system for a fee. It can produce public goods, but ones that are most often related to a specific region or a specific sector, i.e., a seawall that indiscriminately protects all of the people who live behind it. In this last case, the issue is less one of the public/private sharing of actions than that of the distribution of responsibilities between national and local public authorities.

Economic theory suggests that in an ideal world, private goods would be produced by the individuals or firms that benefit from them, and not by governments. For example, if an individual installs an air-conditioner in his home, he will take advantage of it during the next

[8] In economic terms, a good is considered to be public if it is both non-rival (the fact that someone consumes it does not prevent others from consuming it) and non-exclusive (it is not possible to prevent someone from consuming this good). Climate quality is typical of a public good since the fact that I can enjoy the climate does not prevent my neighbor from enjoying it as well, whereas it is impossible to prevent someone else from enjoying it.

heat wave. In the same way, if a forester chooses species resistant to climate change today, his future heirs will benefit from this choice because they will have wood to sell.

However, circumstances do exist in which the private production of adaptation by households or firms (sometimes referred to as "spontaneous adaptation") risks being insufficient, and where public intervention for adaptation is justified from the point of view of economic theory for reasons of equity and/or efficiency. The list that follows is adapted from Lecocq and Shalizi (2007).

- **Poor dissemination of available information:** Experience suggests that information that exists on climate change, its impacts and on adaptation options is not available today in sufficiently large quantity, particularly in developing countries. This creates asymmetrical situations in terms of information that may lead, on the one hand, to maladaptation situations (see Box n°1) and, on the other, may stand in the way of good market operation, create location advantages and produce new inequalities (between and within countries). Public authorities and the international community have an important role to play in this case in the production of information (fundamental research, R&D) and in the dissemination of this information between countries and to households, firms and local communities within countries. This point is developed in Section 2.2.1.
- **Barriers to collective action at the local level**: Adaptation often requires considerable cooperation between actors at the local level for the provision of local public goods (irrigation networks, seawalls, etc.). This is particularly true for the management of transborder resources such as large drainage basins. Public action and international coordination may be necessary to facilitate negotiations between concerned stakeholders. Coordination support may be provided, for example, by the setting of standards and norms (Section 2.2.2), as well as by an action on institutions (Section 2.2.3) such as the creation of discussion forums or national or international mediation activities.
- **Decision routines and inadequate consideration of long-term consequences on private investment decisions:** Private investment decisions do not always adequately take long and very long-term consequences into account (for example, future snow conditions in medium-altitude ski resorts), which could justify public action. In the same way, the provision of basic services by public authorities is often taken for granted, whereas major changes in climate conditions could make these services impossible or too costly (for example, access to water for agriculture on the long-term). This could justify a public action to make it easier to address this new situation.
- **External impacts**: Some adaptation actions are not profitable from the private point of view but may be for the community at large. For example, it may not be profitable for a homeowner to insulate his home to reduce energy consumption linked to air-conditioning, whereas the collective benefit is considerable if a large number of homeowners do it. In contrast, it may be profitable for a developer to build in a flood-prone area, whereas the cost of flooding for the community is much greater (pressure on the healthcare system, temporary relocation of flood victims, etc.) [(9)]. **An optimal**

[9] Many other examples of external impacts linked to adaptation actions exist. Concerning water, for example, it may be economically viable to increase irrigation for agriculture, but the removal of additional water could have negative effects on other stakeholders (particularly electricity producers) and on ecosystems. Once again, in relation to water, upstream actions involving drainage basins, particularly at the transnational level, can positively or negatively influence the situation downstream. In the area of energy, the massive use of air-conditioning or the desalination of seawater can increase energy consumption and lead to tension between adaptation and mitigation. In contrast, the reinforced insulation

action for a stakeholder may therefore have negative external impacts on other stakeholders and not correspond to the socially optimal action, thus requiring public action in order to avoid these effects induced *ex ante*, through, for example, standards, tax measures or institutions (Sections 0 and 2.2.3).

- **The role of major infrastructure networks for the public benefit:** Among the assets to be protected from climate change are networks (rail, road, communication, energy, information, etc.) that can be considered as public goods (as well as high fixed costs). Protecting these networks from climate change is all the more important since they generate important returns for society by providing essential services such as energy, transportation and communications – services whose production must be ensured, even during crises. In addition to standards that make it possible to influence private action in these sectors, adaptation also concerns public investment (Section 2.2.4).
- **Inadequacy of existing standards and regulations**: Some economic sectors are highly regulated, to the point that stakeholders may not react to climate change since they only take environmental and climatic aspects into account by complying with fixed regulations and standards. This is largely the case in the civil engineering sector, for example. In such situations, we cannot expect spontaneous adaptation without additional incentives, and public action is therefore necessary for adaptation, either by modifying the standards and regulations so as to take climate change into account, or to delegate adaptation to the stakeholders by changing regulatory limits so that spontaneous adaptation becomes possible [(10)].
- **Poverty and budget constraints:** The preceding interventions are related to the efficiency of resource allocation. However, another major reason that justifies public intervention is equity. Some individuals, firms, local communities and even countries may be unable to afford adaptation measures themselves, even if these measures are in their own interest. Government (local, regional, national or international) may want to help these actors through transfer mechanisms, e.g., fiscal (see Section 2.2.2), or international transfers.

To sum up, despite the fact that adaptation yields mostly private or local public benefits, economic theory recognizes several scenarios in which public action is justified. However, this is not always the case, and a case-by case analysis is necessary. Government should therefore only support anticipative adaptation measures if the benefits to society outweigh the cost of their implementation. Public cost-benefit analysis provides a framework for making such assessments. This tool is discussed in greater detail in Section 5.

2.2. Types of public action for adaptation

The preceding discussion suggests four main types of public action in terms of adaptation: (1) the production and dissemination of information; (2) action in relation to standards, regulations and taxation; (3) action in relation to institutions; and (4) action in relation to public investment decisions. Adaptation public action is therefore far from being reduced to large expenditures in capital or in infrastructure. We will see, in fact, that some types of action can be effective at practically no cost.

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of buildings that makes it possible to improve the comfort of dwellings in the event of extreme heat or to reduce heat consumption in winter is, on the contrary, an example of synergy between these objectives.

[10] Since standards are generally established to compensate for a lack of incentive, delegating adaptation to stakeholders can only be done by establishing adequate incentives.

This section describes each type of action in detail. It is general (the types of actions discussed above apply to local, national and transnational adaptation policies) and does not deal with the spatial scale of the governance structures the most effectively adapted to the establishment of these actions since they are context-specific and largely dependent on the institutional organization of the territory being considered as well as the result of specific collective choices, e.g., in terms of risk aversion or redistribution choices.

2.2.1 Production and dissemination of information

One major responsibility of public authorities concerns the production and dissemination of information about climate changes, their impacts and how to adapt to them. **Fundamental research** is answerable to public action since the results of fundamental research are generally public goods. Governments have many means to encourage the production of knowledge relevant to impact assessment and for adaptation, whether it be alone or within supranational frameworks. The challenge is to provide a sufficient quantity of fundamental research and useful technologies in time for adaptation to develop.

Notwithstanding a survey, we can expect that the private sector will take charge of part of the R&D effort concerning **technical innovations** as soon as it is able to reap some of the resulting benefits (for example, by developing and then marketing plant varieties more resistant to drought). The issue for the national and international community will be, if applicable, to identify areas where important society-related adaptation technologies would not be developed by private innovation [(11)]. A related issue will be to arbitrate between support for innovation in the private sector (objective: economic development) and the transfer of adaptation technologies towards stakeholders and countries that themselves do not have the means to obtain them on the market (objective: solidarity and development aid).

Second, public authorities must ensure the dissemination of information on the impacts of climate change and on ways to adapt to it. The difficulty here is that this information is compartmental, controversial and constantly changing with scientific progress. Even though it is available in scientific publications, it is quite costly to organize and format in a language that can be used by decision-makers. In France, a specific institution, the ONERC or French National Observatory of the Effects of Global Warming, has been responsible for making this information accessible since its creation. In the United Kingdom, the UKCIP program handles both research and accessibility of information to businesses, regional government agencies and households. It is obvious that many developing countries cannot devote the same efforts to these issues, and support for the international dissemination of information is therefore of utmost importance. This issue is discussed at the international level, i.e., though the Global Framework for Climate Services, established within the framework of the World Meteorological Organization.

Nevertheless, the information necessary will be very different depending on the regions and sectors considered. Within this context, a complementarity between the public sector and the private sector should be established. The first should disseminate general information on climate scenarios, impacts and adaptation at a minimal cost since this information can be considered as a public good. The second (with the eventual collaboration of public institutions) could provide more detailed analyses by region or by sector, since these analyses require a specific effort and have a significant marginal cost. This hypothetical situation, however, raises several questions. First of all, this detailed information must remain accessible to local stakeholders with less ample means – which could require the implementation of specific measures (e.g., subsidies). A second issue concerns the validation and verification of the

[11] We can make an analogy with the under-investment of pharmaceutical firms in the battle against malaria – highly prevalent worldwide – relative to their investment in the fight against other diseases that are more prevalent in high-income countries.

quality of information distributed, within a context where the time scales involved do not always allow for feedback in terms of experience or the reputations of producers of poor-quality information. Box n°2 gives an example of the strategic role of information for making decisions in the case of private stakeholders.

Box n°2: The impact of information on competitive conditions: the case of ski resort operators

The OECD has studied the link between global warming and winter sports (Agrawala, 2007), revealing the importance of the role of information on market operation and competitive conditions between stakeholders.

There are currently 660 ski resorts in the Alps, with revenues that make it the number one economic activity in the region. However, this environment is particularly sensitive to global warming: the Alps are one of the areas of Europe where the temperature is increasing the most rapidly. Historical series show that the temperature increase in this region was more than 50% greater on the average than the global warming average worldwide over the past 40 years. To adapt to global warming, ski resort operators are therefore confronted with a double uncertainty: (i) the overall global scenario, and (ii) its transposition to local conditions with a very high probability of a global scenario with a rise of 2°C, which translates into a rise of over 3°C above the ski slopes.

A recurrent snow shortage has caused problems in 60 of the resorts. If the temperature rises by an average of 2°C over the next decades, the OECD estimates that some 100 additional resorts will suffer from a lack of snow. If it rises by 4°C, only 200 resorts will be able to operate – those located above 2,000 meters.

These resorts spontaneously turn to the production of artificial snow. This type of spontaneous adaptation increases the amount of energy used, upping operating costs and emitting greenhouse gases. It requires water – over 10 million m^3 each winter in France – representing a considerable cost. And then there is the prime ingredient for the snow cannons to work: cold. When the thermometer refuses to go any lower, the snow cannons remain idle and the skiers have to go to slopes at higher altitudes or revert to hiking. The return on investments made in the name of adaptation is therefore the inverse function of the seriousness of the impact that it is supposed to correct.

From an economic point of view, the impact of global warming on operating conditions in ski resorts in the Alps can be analyzed as a loss for the sector in general. In the beginning, it takes on the form of an increase in production costs. It then represents a loss in capital with the likely closing of low and medium-altitude resorts. However, it is important to note that this loss modifies the competition, creating winners and losers.

Overall sector losses will be the result of multiple adjustments between certain stakeholders who will take advantage of the situation and others who will be weakened and sometimes doomed to disappear. Competition rules will be modified: the future of operators specialized in medium-altitude resorts that cannot re-orient their activities will be compromised; operators specialized in higher altitude resorts will, in contrast, benefit from the shift in clientele and cost-related advantages. If we study the structure of the sector, we can see that a limited number of operators intervene in several areas and specialize in high-altitude resorts, especially the largest ones like the Compagnie des Alpes, traded on the Paris stock exchange, that recently refocused its investment strategies on high-altitude ski resorts because of global warming. Low and medium-altitude ski resort operators are currently being abandoned by the major operators.

Past information dissymmetries have made it possible for some of the better-informed stakeholders in the sector to make high-altitude investments that will allow them to benefit from a comparative advantage over other operators in the sector for several decades. In light of the consequences for the entire region, given that a large part of the population lives off of winter tourism, these questions are not only relevant for private actors, but they require a more in-depth public reflection.

A third important type of public action deals with the detection of early warning signs of climate change. In light of the temporal inertias described above, it is important that all of the information that can be drawn from the observation of local impacts on climate change be interpreted as rapidly as possible in order to expand the shared body of knowledge on climate change impacts. This detection of early warning signs requires adapted institutions (see Section 2.2.3).

2.2.2 Adaptation of standards, regulations and tax measures

The adaptation of existing standards and regulations in relation to future climate changes is an obvious enough requirement for everything that concerns adaptation of long-term fixed capital (buildings, infrastructure, transportation, civil engineering works, etc.). However, revising public standards in view of climate risks is an issue that concerns many other economic sectors.

Concerning long-term fixed capital, the government typically fixes (implicitly or explicitly) the **acceptable risk level**, via, for example, dimensional standards for civil engineering works, standards related to new constructions [(12)], or by limiting constructible areas. These standards are generally based on the past frequency of natural disasters, frequencies that no longer correspond to the present risk and still less to future ones. In the case of building standards in civil engineering, for example, regulations generally indicate the expected level of resistance for the stakeholders, most often calculated using historical data [(13)]. With climate change, these standards must evolve. Two solutions can be considered. In the first solution, the public sector establishes a procedure for updating the standard on a regular basis so that it is always up-to-date. In the second solution, the public sector delegates this job to economic stakeholders by establishing standards that "follow" (or "precede") the climate. For example, in relation to civil engineering structures, the public authorities can require the capacity to resist 100-year floods as a standard, without specifying the level of this flood, leaving this to the economic actors. In reality, this would require the government to develop procedural standards to ensure that this risk analysis is carried out correctly, as was done with a varying degree of success for prudential regulations in the financial sector [(14)].

In addition to technical standards *stricto sensu*, it may be necessary to adapt **procedural standards**, e.g., making a vulnerability/robustness study in view of climate change mandatory for public and private civil engineering works [(15)]. From a more general point of view, facilitating adaptation may also involve the modification of other **standards not directly linked to climate risks but that have an impact on adaptability**. In the case of long-term fixed capital, architectural and development standards therefore play a critical role. In Paris, for example, window shutters were forbidden for 30 years in the name of urban landscape protection. Likewise, overly restrictive regulations related to open spaces can discourage tree planting in cities, essential for dealing with steep rises in temperature. By examining possible changes in these standards, decision-makers (local as well as national) face the challenge of distinguishing between the aim of facilitating adaptation to climate change and other objectives

[12] These standards make it necessary to establish a link with other policy objectives like, for example, those related to the reduction of energy consumption in the building sector.

[13] Since this information is similar to a public good, it is justified for the government to distribute it freely (see Section 2.2.1).

[14] Since the Basel II accords, financial regulators have delegated the responsibility of proposing risk models to private actors. This type of regulation is now being extended to insurers (Solvency2).

[15] The World Bank, the French Development Agency and most of the other bilateral development agencies are developing procedures to tests for climate change vulnerability into their project cycles for projects that involve long-term capital (particularly infrastructure).

to which these standards correspond, such as the protection of urban landscapes or risk management linked to open spaces.

Finally, we cannot overlook the existence of implicit routines, habits and standards that influence the operation of organizations, firms and households. These routines and standards cannot be modified upon a simple decision. On the contrary, their evolution will require different actions in terms of information dissemination and education (particularly within professional development). In some cases, these standards and habits are highly inert. In others, they can be extremely rapidly modified, like in the case of smoking in public places. In addition to public standards, other economic instruments such as taxation may motivate economic agents to modify their routines. For example, regulations concerning the property tax system have a particular importance since they can lead to different types of land use and different levels of natural risk exposure.

2.2.3 Adaptation of institutions

A third type of public adaptation measure concerns institutions. The typology established by the 2003 World Development Report of the World Bank attributes three essential functions to institutions within the context of environmental change: identifying early warning signs of changes and crises, balancing the interests of the different stakeholders, and being capable of credibly implementing the solutions it proposes (World Bank, 2003).

Identification of the early warning signs of the impacts of climate change has already been discussed in the section concerning information processing. It is of utmost importance since the earlier these signs are identified, the wider the panel of adaptation measures available to the community will be. Within this context, it is necessary to verify, on the one hand, that existing institutions do a good job of collecting relevant information to identify the signs linked to climate change, and on the other, that this information is cross-referenced and processed in time to provide ample warning that can be put to good use. If necessary, particularly at the regional level, new institutions or new arrangements can be created. New information technologies provide tools at this time to carry out these operations, e.g., via satellite imaging or the creation of decentralized systems to monitor the state of ecosystems, inspired by the medical monitoring network model, in order to provide additional support for existing institutions.

The ability to produce well-balanced arrangements is critical since existing institutions may be subject to increasing pressures as a result of climate change. For example, water distribution among users may become even more conflictual in the future than it is today. Similarly, the impacts of climate change may create tensions between public-private partners (PPPs) as a result of the emergence of unforeseen risks in the initial arrangement [(16)]. Within this context, it may prove necessary to review existing institutional arrangements, or even to create new ones. For example, by exacerbating tensions between supply and demand on the electrical power grid, climate change may require a greater degree of cooperation between European stakeholders in the sector.

The **credibility of arrangements and the ability of institutions to enforce them** is a general problem that is not specific to adaptation to climate change. In contrast, given that a high degree of uncertainty exists about climate change damages and the fact that information is rapidly increasing, arrangements must be sufficiently **flexible** to be able to adapt to new circumstances if they are to be sustainable. The definition of "adaptive" standards (see the preceding section) is an example of the way in which this flexibility can be integrated into

[16] In this case, the literature emphasizes the importance of the flexibility of contracts to allow beneficial re-negotiations for both parties in the event of a change in circumstances (see e.g., Cochran (2009) for the case of transportation infrastructure). However, we must also be careful not to allow climate change to become a pretext for opportunistic re-negotiation demands on the part of firms, a frequent problem in public-private partnerships (PPP) (Irwin, 2007).

contractual arrangements. Introducing geographically flexible elements is, in particular, a major challenge within the framework of climate change. Here once again, particular attention must be paid to moral hazard issues if the government agrees to help some stakeholders with their adaptation in the event of a very negative impact. It is crucial not to create perverse incentives that would encourage stakeholders not to anticipate their adaptation and to use the impacts to justify public aid.

Institutional measures must play an important role in all adaptation strategies. This can be illustrated by a comparative analysis of the reaction of Louisiana and the Netherlands to the local rise in sea level of 50 and 20 cm, respectively, during the 20th century (Hallegatte, 2010). Holland's successful strategy since 1953 is due more to the establishment of institutions necessary for risk management (the Delta Commission) than to the implementation of technical measures (seawalls, etc.). These institutions actually guaranteed risk management and the reinforcement of protective measures on a regular basis, instead of management on a case-by-case basis, consisting of reinforcing seawalls after each disaster, as observed in Louisiana.

To ensure that institutions play their role in the adaptation to climate change, an essential prerequisite is to precisely define responsibilities. Although adaptation will be of concern to a large number of existing organizations and institutions, responsibility for it will not necessarily be automatic or planned. We must therefore make sure that contradictory initiatives are not taken by several organizations that decide to tackle adaptation to climate change without consulting other organizations beforehand, and that certain issues are simply not addressed because one of the possible stakeholders did not do so. This question is particularly sensitive in relation to the definition of relevant spatial scales. Whereas adaptation implies territorial policy choices that must certainly be defined at the local scale, it also requires coordination between territories to avoid costly incoherencies. The implementation of effective adaptation strategies will therefore depend on the mobilization of existing institutions and their competencies, as well as on coordination tools that will make it possible to take advantage of sectorial or regional initiatives, while avoiding contradictions and inconsistencies.

Another area in which institutions should adapt is that of crisis management (reactive adaptation). In the event of a disaster or crisis, an emergency response often requires means beyond those of the region or country hit. It is therefore useful to pool these emergency means, as European countries do, for example, to fight forest fires. The same problem arises during reconstruction since the lack of capacity sometimes leads to an increase in prices and a slowdown in reconstruction (as was observed with the 2004 and 2005 hurricane seasons in Florida, or after Katrina in Louisiana; see Hallegatte, 2008). At this stage, it is sometimes possible to take advantage of reconstruction to improve the situation, i.e., by improving transportation networks or the quality of buildings instead of rebuilding the same ones (which is done in the large majority of cases). However, this presupposes that reconstruction actors have the resources necessary for "intelligent" reconstruction and the time to implement it, often without the income from their normal activity that was interrupted by the disaster. These financial resources can be provided by an effective insurance fund or through targeted public aid [(17)]. Adapting crisis management systems is one of the "no regret" measures that contribute to adaptation to climate change since they can generally be justified by existing natural risks, even in the absence of climate change.

[17] We can imagine specific funds to help countries hit by a disaster, on the model of the European Union Solidarity Fund, or the Caribbean Catastrophe Risk Insurance Facility (CCRIF). We can also imagine more general types of mechanisms such as "rainy day funds", i.e., special public funds where excess revenue is set aside when available for use in times of unexpected revenue shortfall or budget deficit (Lecocq and Shalizi, 2007). These funds exist in several states in the US and in some developing countries.

2.2.4 Adaptation of public investments

For central and local governments, the three types of actions described above consisted in creating an adequate environment to enable and promote private adaptation. However, central and local governments are also directly involved in adaptation in their role as owners and operators of long-term fixed capital (buildings, infrastructure, etc.), as well as in their role of ecosystem manager, employer, etc. **A fourth type of public measure in view of climate change therefore deals with the adaptation of existing public infrastructure** (transportation networks for passengers, merchandise and energy, telecom networks, etc.), as well as public buildings in general. New investments must also be adapted, e.g., in terms of size and location. More generally, this type of action covers policies that structure land use, whether it be for urbanism policies, major investments (transportation of goods and merchandise, water transport, etc.), regional economic development projects, etc. In the end, the question of relocating activities and populations will also arise (see Section 2.3.2).

2.3. Examples of possible adaptation measures in several major sectors

Public action in relation to adaptation to climate change covers some new and specific actions such as access to information on climate scenarios or a compendium of climate change warning signs. However, we have already seen that the majority of public actions targeted at adaptation consist of modifying public policies so that climate change is correctly taken into consideration in the decisions of public and private stakeholders in each economic sector. **The aim of this section is to illustrate the major categories of adaptation measures described above using sectorial examples.** It must be remembered that these are only examples and that this section in no way aims at being exhaustive. First, many sectors are not examined here. Second, the discussion within each sector focuses on only several examples. A specific study would be necessary to identify and validate possible adaptation measures and to build an adaptation strategy for each of the sectors considered.

2.3.1 Construction and urbanism

To illustrate the influence of inertia and uncertainty on investment decisions, it is interesting to focus on sectors with very long-term capital. These sectors include building and urban infrastructure that are discussed in this section, as well as the energy sector and that of transportation that are presented in the following section. In these sectors, capital – whose lifespan is on the same order of magnitude as the climate change time scale – must remain productive despite a climate that will undergo considerable change. This challenge does not only concern new investments but also, and above all, a large part of the structures and infrastructure already installed that intend to remain productive for several decades to come.

As mentioned above**, the very long lifespan of capital complicates the definition of adaptation measures**. Thus, a building built in 2000 with a lifespan of 150 years should be adapted to the current climate in Paris, as well as to the climate in Paris in 2150, which will probably be very different from the climate today. We know how to build buildings adapted to different climates, but it is more complex to build a building (or any other infrastructure) adapted to a wide range of climates rather than a well-defined specific climate. The challenge is therefore either to reduce the lifespan of the capital (existing as well as future), but at the risk of high replacement costs, or to build more robust structures capable of adapting to different types of climates, but at higher initial costs. Moreover, the risk of maladaptation is greater when the lifespan of the capital is particularly long (see Section 1.2 and Box n°1).

Urbanism involves even longer time horizons because the structure of a city (e.g., in terms of density) is an almost totally irreversible choice. Moreover, action is difficult in this sector, as demonstrated by the multiple failures in this area and problems to control rapid and uncontrolled urbanization in cities in developing countries where the large informal sector, real estate pressure and the absence of land tenure make classic land use and urbanization policies almost totally ineffective.

To orient the investment choices of private and public stakeholders toward a lower climate-vulnerability in the building and urbanism sectors, the important role of standards and regulations has already been mentioned (Section 2.2.2). However, adaptation in sectors with long-term capital also involves the management of institutions (Section 2.2.3) to ensure, for example, the stability of public-private partnerships, and, of course, the choice of public investments *stricto sensu* (Section 2.2.4).

2.3.2 Energy and transportation infrastructure

Energy and transportation networks play an unquestionable role for the public at large, and their extended interruption would generate considerable costs for the economy as a whole. Their operation depends on infrastructure with very long lifespans (a significant part of the French national road network is built on former Roman roads). It is within the scope of public action to ensure that these infrastructure adapt to climate change.

Energy infrastructure, for production as well as transportation, are often located in areas that are highly vulnerable to climate change as a result of their proximity to water and the sea. This proximity is linked as much to technical constraints (cooling) as to economic constraints (access to ports and sea routes). A first stage of adaptation will therefore be to ensure that this infrastructure effectively resists future climate constraints. It should also be accompanied by action that takes account of the high sensitivity of energy supply and demand to climate conditions and climate change.

Adaptation measures to be taken in this sector are mainly focused on changes in planning procedures and technical criteria in order to better prepare new infrastructure for climate change, as well as on rehabilitation and, in some cases, on the protection of existing infrastructure. The success of these efforts will depend on the capacity of a certain number of stakeholders involved in the design, construction, maintenance and operation of transportation infrastructure to develop and to implement coherent approaches. In other words, the institutional challenge is central to the issue.

2.3.3 Water and agriculture

The case of water management provides an example of the role of standards, as well as the importance of interactions between sectors, especially in terms of energy, water and biodiversity.

Many standards and regulations can actually be used to control the level of water demand, e.g., by fixing acceptable levels of withdrawal or – in extreme cases – deciding that some activities that consume large quantities of water (particularly those related to agriculture) are not acceptable in water-scarce areas. It is also possible to use economic instruments such as the price of water that will act as a price signal to indicate the scarcity of the resource and to promote the efficient use and withdrawal of water. The challenge here is to solve potential conflicts between different uses, and take in account arbitrations between various economic sectors (electrical, agricultural, industrial and domestic production) and the maintenance of the flows necessary to preserve ecosystems.

Agriculture is one of the sectors most directly affected by climate change. Adaptation will take place progressively at the level of economic agent through modifications in agricultural practices (e.g., by modifying planting dates or by using more heat-resistant varieties) and by changing the nature of production itself with a probable shift of agricultural crops towards the north in the Northern Hemisphere (and towards the south in the Southern Hemisphere). In some cases, we can also expect net gains for some crops and some regions, at least for a limited warming in the first part of this century. These individual adaptation actions will nevertheless require public action, if only to make them coherent with water and land-use management policies. Moreover, some adaptations will be difficult to carry out at the individual level alone. For example, the creation of new sectors will undoubtedly be necessary, and to do this, coordination at the national level could be useful in conjunction with professional organizations. Specific cases will require specific actions, such as Controlled Appellations ("Appellations d'Origine Contrôlée or AOC)", whose definition is based on a terroir and a climate and that may have to be modified, for example, in the case of wine. It should however be observed that many decisions concerning agriculture are made for relatively short time horizons and do not require immediate action.

2.3.4 Ecosystems

Likewise, public policies for managing **ecosystems will have to be reviewed to ensure that they are compatible with climate change.** Ecosystems threatened by climate change (wetlands, forest areas, etc.) actually produce many environmental services that are of benefit to the community (air and water quality, protection of biodiversity, etc.), and public intervention is necessary in this case to ensure that these functions are "produced" in sufficient quantity. Public action is both indirect (e.g., management standards for private forests) and direct (e.g., public service management of some forests or particularly valuable environmental zones such as natural parks or coastal zones). The problem is nevertheless very complex because the response of ecosystems to climate change is still poorly known. The central challenge is the localization of ecosystems (and, therefore, the institutions that protect them like national parks, etc.) that may change in the future, making it perhaps necessary to modify land use and, more generally, to modify the geographic perimeter of certain activities.

Forest ecosystems offer a particularly interesting example in this case. Due to the complexity of these ecosystems, the need for R&D is considerable in order to more effectively detect and understand the impacts of climate change on forest ecosystems and adaptation strategies, especially the introduction of more robust species or even exotic ones [(18)]. When the lifespan of certain forest species is on the same order of magnitude as that of infrastructure, public investment (the choice of species in this case) raises similar decision problems in situations of uncertainty. Management standards and regulations, particularly those concerning taxation, play an important role in this decision and must be reviewed within the context of climate change. Finally, climate change raises the question of forestry institutions and, in particular, the cooperation capacity within forest massifs characterized by a high degree of fragmentation of private forest property.

These aspects are even more important since **ecosystems are not just a capital to be protected from climate change but can also be mobilized to strengthen the adaptability of our societies to this change.** This is the principle of "ecosystem-based adaptation". Thus, natural wetlands very effectively provide protection from storm tides and exceptionally high tides, and can take the place of or supplement a seawall or another hard structure, therefore avoiding or reducing its negative impacts on biodiversity, erosion, landscapes or tourism. This type of approach is used around New Orleans in an attempt to restore wetlands that were destroyed during the last centuries.

2.3.5 Insurance

The role of regulation can be illustrated in the case of the insurance sector, effectively demonstrating that adaptation is not just a question of investment and infrastructure. From the point of view of insurers and reinsurers, climate change involves many modifications of practices that will probably have to be integrated into regulation modifications for the insurance sector. First, the actuarial approach to the probability of the occurrence of a natural disaster is no longer valid since the climate is changing. This may make it necessary to abandon

[18] In the French case, see Roman-Amat (2007), for example.

approaches based on historical data and use risk assessment models instead. This was actually made mandatory in Florida after Hurricane Andrew in 1992. Second, the increase in the probability of occurrence of extreme events and the potentially higher correlation between risks make default risks greater for insurers and *in fine* for reinsurers, eventually justifying higher level of reserves. The insurance sector is very highly regulated in all countries, and these changes will lead to modifications of these regulations. In some countries, the central (or local) government is also a stakeholder in the insurance or reinsurance sector. This is the case in France with the CAT-NAT system in which the government is responsible for losses linked to most natural disasters (with the notable exception of storms), as well as in Florida where the public insurer, Citizens, has a large share of the market, following the withdrawal of a large number of private insurers unable to face ever-increasing risks.

More generally, insurance can also be considered as a tool for adaptation. In particular, a high penetration of insurance allows economic stakeholders affected by a disaster to rebuild more rapidly and to avoid bankruptcies (particularly small businesses), and to therefore get the economy back on its feet more rapidly, limiting indirect economic losses (see an example on Mumbai in Ranger et al., *forthcoming*). Moreover, the presence of insurance (particularly for operating costs) enables stakeholders to proceed with reconstruction in a more peaceful atmosphere and to therefore seize improvement opportunities, i.e., to reconstruct "better" rather than reconstructing "identically". Finally, access to insurance against natural risks also allows some stakeholders to take higher risks as a result of the fact that it is shared and transferred to stakeholders who can handle it. The risk can appear as a production factor, making it possible to strengthen the producers' position. Thus, better risk distribution, thanks to insurers, increases the economy's ability to make the changes necessary to adapt to climate change.

In theory, if insurance rates were representative of the risk level in a given area, access to insurance could also be used to provide information on their level of risk to businesses and households. This information would be communicated in the form of a price signal that they are not necessarily able to evaluate for themselves. This is not the case in France today where insurance rates for natural disasters are identical in all areas, at-risk or not. However, the idea of insurance rates determined in relation to risk level is controversial. Basically, the transition from a fixed-rate system to a system where rates are based on risk level is complex since it could lead to very steep price increases whose political acceptability is uncertain. Moreover, even outside of the transition phase, insurance rates directly related to risk level can lead to difficulties for the poorest households that sometimes settle in the highest risk zones where real estate costs are lower. An increase in insurance rates could therefore eliminate this possibility, leading to the absence of insurance or increased difficulty in finding housing.

In general, the question of natural risk insurance cannot be separated from questions of access to housing, the cost and availability of real estate and land-use planning. The example of Florida shows that insurance rates that are strictly determined by the level of risk can endanger the economic viability of some regions, with highly negative consequences for the populations concerned. Moreover, hazard-prone areas are not only associated with private advantages (such as a view of the sea), but also provide collective benefits (as in the case of port areas that are at risk but that make it possible to decrease the cost of imports for the population as a whole, like in the case of New Orleans). Mixed solutions that take account of the risk level to create price signals while maintaining a high level of national solidarity can be considered in order to reconcile these different requirements. However, these measures could only be initiated if they are highly consistent with land-use policies and, particularly, with zoning policies (i.e., the definition of hazard-prone areas in which limitations on construction apply).

3. The territorial and spatial dimensions of adaptation

An important particularity of adaptation strategies is their spatial dimension. **An adaptation strategy cannot just address different sectorial needs but must integrate the different components of public action within an integrated territorial vision.** Thus, three main questions arise: (1) How to anticipate and manage changes in the localization of activities and populations (Section 3.1); (2) How to integrate the international impacts of climate change into national adaptation plans (Section 3.2); and (3) How to distribute adaptation efforts between the different regions and territories (Section 3.3).

3.1. Maintain the status quo or take a new direction?

In Section 1.2, we saw that maintaining identical activities or services can be too costly or even technically impossible in some cases. In these cases, adapting to climate change requires a change in development trajectories. **This bifurcation can either take the form of a change in location or that of a change in activity at the same site.** An extreme example of location change is illustrated by some island states in the Pacific Ocean that may no longer be inhabitable at some point in the future if the rise in sea level exceeds a critical threshold. Likewise, the impacts of climate change in some coastal areas may lead to the same type of relocations on the long-term as well. The question is to know when and how to prepare for this type of change.

3.1.1 Changes in activity

An **example of a possible change in activity at the same site** is provided by some countries in the Mediterranean region, major tourist destinations that could encounter difficulties in handling a drop in the tourist flow if summer temperatures go above a certain level (e.g., Bigano et al., 2008). Given the importance of tourism for the development of certain regions (exceeding 8% of the GDP in many countries in the Southern Mediterranean such as Morocco and Egypt), the consequences would extend well beyond the tourism sector and would have an impact at the macroeconomic level. Since many regional economies today are based on specialized sectors that are vulnerable to climate change, they need to find alternative development trajectories at the regional scale.

Economic history suggests that specialized economies are very vulnerable to changes in variations in the profitability of their main economic sector. In French regions where mining activity disappeared in the 1970s, or in deindustrialized regions of the United States, the economy remained depressed for long periods of time in spite of the high-level financial support provided at the national and federal levels. These experiences show that specialized economies have a limited capacity to deal with profitability shocks by transferring their resources to new sectors. Beyond a certain threshold, the "transition capacity" is exceeded: the level of education of employees in the sector concerned may become insufficient for the development of new sectors, and the investment capacity in new sectors may be too low. Problems linked to investment capacity are particularly important when regional revenues decrease as a result of the drop in profitability of the main sector of a specialized economy.

When designing an adaptation plan, it is therefore necessary to distinguish marginal disturbances that require a simple adjustment of practices, and structural changes made necessary by climate change. Public action and transition support will be especially necessary in these latter cases that should be carefully identified.

3.1.2 Relocation of populations and activities

An example of geographic shift concerns the withdrawal from zones at the highest risk of flooding, e.g., due to the rise in sea level. In some sparsely-populated coastal areas, it is more rational to withdraw inland than to try to protect the area at any price. However, avoiding densification of these areas and carrying out such a withdrawal raises technical, economic and political problems.

In an ideal world, with perfect foresight, we could imagine that this withdrawal would take place naturally, with the value of assets and investments regularly decreasing as the risk in the zone increases. At the time the zone should be evacuated, the assets would be at the end of their lifespan (i.e., totally depreciated) and would therefore have a zero value. In this case, the cost of withdrawal would be null. However, this is difficult to imagine for three reasons:

- First, an urbanized zone is composed of many types of assets (housing, roads, water supply systems, etc.) that have very different lifespans, and it is difficult to imagine that all of these assets can arrive at full depreciation at the same time.
- Then, it is not possible to stop all maintenance and to live in housing that deteriorates over time and whose comfort is compromised. Likewise, it is not possible to live with roads whose quality (and, as a result, safety) deteriorates over time so that they reach the end of their lifespan at the time that withdrawal takes place. Even if we establish a minimal threshold of acceptable comfort and/or safety, it is not realistic to schedule investments so that we arrive at total depreciation (financial) of the asset and at a given level of comfort and/or safety, due to uncertainties about asset degradation dynamics. We can clearly see that this approach is not realistic and that we cannot avoid abandoning assets that are still usable (with, therefore, a non-zero cost).
- Finally, scheduling investments so that the asset is depreciated at the exact time the withdrawal is necessary would require perfect foresight and an error-free evaluation of the rise in sea level, which is totally unrealistic.

An anticipated withdrawal from hazard-prone areas is therefore unlikely without public action to coordinate it, and it cannot be done at low cost. On the other hand, local governments can implement a concerted action (a "strategic withdrawal") in conjunction with urbanization plans, measures taken by the coastline protection board, and public policies governing investment in infrastructure. Such an anticipated and strategic approach may be able to reduce significantly the cost, with respect to a reactive and non-coordinated withdrawal.

3.1.3 Methodological and institutional implications of economic bifurcations and transitions

From a methodological point of view, it is more complicated to assess economic shifts and transitions than to assess marginal or incremental changes. In fact, the comparison of two economic equilibrium states that are very different from each other requires multisectorial economic models that do not always exist and whose use remains complex. Secondly, two economic equilibria that are very far from each other can be difficult to rank from an economic point of view [19]. If tourism stops being a viable economic activity, it can be replaced by many different sectors (from manufacturing to services, for example), and it is not easy to decide which alternative activity is the best in terms of population welfare. Moreover, **assessing the difference between two economic trajectories is often a question of measuring transition costs, not differences between final equilibria.** If tourism as a main local activity has to be replaced, the question is not really whether manufacturing or services are better alternatives. The question is how one can create these alternative activities, and at which cost. These transitions are more difficult to evaluate because they require dynamic models.

On a larger scale, **we are dealing here with institutional questions about the way in which territories can design their future and their development strategies.** This is an exercise in which all of the economic development dimensions must be taken into account.

[19] In Hourcade and Kostopoulou (1994), we can find an example in the energy sector (see the discussion of changes in development trajectories in Najam et al., 2007).

However, the breakdown of responsibilities in different sectors (water, energy, risks, etc.) makes it difficult to manage this type of exercise. Climate change could nevertheless precipitate and facilitate reflections in this area. In particular, a link must be developed between adaptation and current ideas on low-carbon or green-growth development trajectories. Bifurcations also acutely raise the question of **accompanying transitions and the management of the distribution effects of bifurcations** at the financial, technical and human levels.

3.2. Adaptation of national territory within an international framework

Adaptation to climate change does not stop at country borders. On the contrary, climate change requires all countries and particularly developing ones, to revise their development strategies in view of climate risks (Shalizi and Lecocq, 2009). The impacts of climate change will be felt throughout the world with the likelihood that the biggest ones will be felt in developing economies or those in transition where resources to deal with them are scarcer (in physical, financial, human or institutional capital). These international impacts will have multiple **induced effects** at the international level that other countries will have to take into consideration in the development of their adaptation strategies.

At the economic level, these induced effects will be transmitted through markets, with implications for **international trade** that will not always be easy to anticipate. Research in the areas of forestry and agriculture in particular nevertheless leads us to believe that the impacts will be significant, with risks and opportunities that will depend on the sectors. With the probable opening of new trade routes in the Arctic Ocean during the two months of summer, we can expect a change in the geography of international trade that we should anticipate in order to take better advantage of it. Moreover, climate change adaptation technologies can also open new markets for domestic firms, especially in sectors where they already have competitive advantages. As previously mentioned, the experience acquired and the technologies available in tropical and sub-tropical countries could be developed in more temperate countries that will have to deal with similar climates in the future. This development will create opportunities for businesses from tropical and hot countries.

The impact of future climate change on **international migration** is potentially very high, even though migration drivers are extremely complex and few migrations are triggered by a unique process. Climate-related migration could concern arid regions located between humid tropics and temperate zones that are highly vulnerable to warming because of water deficits (Southeastern Europe, the Near East, North Africa, Central Asia). Moreover, climate change tends to exacerbate tensions on resources that are already rare, with potentially major implications – negative or positive – in terms of **security** (international water sharing, for example).

To avoid the future conflicts that some authors have warned about (Welzer, 2009), it is essential to associate an adaptation strategy with **cooperation and development policies** (OECD, 2009). In fact, climate change is an additional justification for development aid. Adaptation to climate change will create new needs in terms of development aid and will also require that development stakeholders integrate this dimension into their projects and programs (Agence Française de Développement, 2006; World Bank, 2010). Moreover, the industrialized countries are committed, within the context of the United Nations Framework Convention on Climate Change and the Kyoto Protocol, to support the adaptation of developing countries. Until now, available resources have remained very modest but may increase if the promises made in Copenhagen are kept. Even if these resources are well under the needs evaluated by development agencies, their implementation may reduce the negative impacts of climate change outside of the national territory. If we take the interactions described above into account, this type of process would facilitate the establishment of national adaptation strategies in industrialized countries by reducing the external pressures that exist on these territories.

Implementation of a real international cooperation policy in relation to adaptation to climate change has unfortunately remained a stumbling block in international negotiations on the climate for several years and a bone of contention between developed and developing countries. It always comes back to three questions: the necessary amount of resources, the governance of the institutions responsible for financial transfers, and the distribution of resources devoted to adaptation among the different countries. To some extent, these questions are also found at the national level where it is also necessary to find the means to distribute resources earmarked for adaptation between the different regions and territories.

3.3. Allocation of resources for adaptation between regions and between sectors

The question of knowing how to allocate resources for adaptation between regions and between sectors arises and will arise at every level of decision-making – local, regional, national and international. We illustrate it here with the example of the allocation of resources at the international level, an example that has been much studied and that we can extend to other decision-making levels.

In the case of the allocation of rare resources, the economist's reflex is to allocate the resources to projects whose marginal benefits for society – i.e., the social benefit for the last cent invested – **are the highest**. This picking rule allows us to obtain a portfolio of projects whose benefit is the highest for a given level of resources. However, application of this rule raises two problems: a problem of evaluation and a problem of distribution.

The evaluation problem will be discussed in the following section. In contrast to mitigation measures, no performance indicator exists for adaptation measures. In theory, we can always compare these measures to each other by examining their monetary benefits in terms of damage avoided. However, these benefits are uncertain and not always calculable *ex ante*. Limiting ourselves to adaptation measures that are subject to complete cost-benefit analyses could even be counter-productive since the choice would always be biased towards projects with investments in physical capital, at the expense of "softer" adaptation measures, often effective and less costly, but more difficult to assess with cost-benefit analyses. Solutions exist to ensure fair competition between different adaptation measures, for example, by explaining the advantages and disadvantages of the different measures considered using a multicriteria approach.

The distribution problem is also particularly sensitive. In contrast to mitigation, adaptation benefits are mainly local. **Consequently, we must compare measures whose benefits go to very different individuals** [(20)]. The economist's traditional approach in this case is to consider that, no matter what, we have to choose the most cost-effective projects and then eventually resort to financial transfers to satisfy any equity objective. The problem is that these types of transfers are difficult to imagine at the international level, especially if official development assistance (ODA) expenses and adaptation expenses are separated. Practically speaking, it is likely that international funds earmarked for adaptation are accompanied by an implicit apportionment formula for the major regions of the world, based on equity considerations. It is then up to the international institution responsible for the allocation of these funds to allocate financing in the most effective way possible within the different regions.

An additional difficulty arises from the fact that developing countries demand that resources earmarked for adaptation to climate change be over and above official development assistance

[20] This is nevertheless not always the case. For example, measures favoring R&D in terms of information technology or the supply of information on the impacts of climate change potentially benefit humanity as a whole.

(ODA), in order to limit the risk that the increase in resources earmarked for adaptation be to the disadvantage of ODA. Nevertheless, it is not always easy, in practice, to separate resources earmarked for adaptation from those earmarked for development *stricto sensu*. **A second question is therefore to know if it is necessary to establish a separate compatibility between adaptation and ODA, and if so, how.**

In a small number of cases, it is fairly easy to distinguish adaptation resources from development aid resources. For example, increasing the height of an existing seawall to cope with a rise in sea level is strictly linked to adaptation, **but adaptation and development are generally interconnected.** On the one hand, adaptation and development aid are often financed within the framework of the same project, e.g., a rural development project that contains an adaptation component. Moreover, adaptation and development cannot always be distinguished in reality. For example, education has an impact on the ability of individuals to adapt, but it is impossible to determine the actual "share" of an education project that is devoted to adaptation.

In theory, a possible approach would be to identify the "additional cost" of a development project, compared to its cost if climate change were not taken into consideration. However, in order to determine this difference, it would be necessary to build a hypothetical reference situation "without adaptation". In addition to being time and resource-consuming, this construction could just be impossible if adaptation and development are linked, or if the presence of climate change leads to a shift in activities. In the latter case, the project "without adaptation" would be totally different from the project actually implemented.

Subsequently, the separation between resources earmarked for adaptation and those linked to development appears to be a major risk for the implementation of development projects. It is of utmost importance to be able to define simple methods to calculate the share devoted to adaptation in development projects in order to (i) reduce transaction costs in project finance, and (ii) avoid a bias in favor of adaptation measures *stricto sensu* (i.e. without development co-benefits), at the expense of adaptation measures linked to development projects (i.e., with development co-benefits).

This discussion also has implications for the allocation of resources at the national level. It suggests that it would be ineffective to base adaptation policy on a single dedicated budget managed by a single ministry or government agency, but that it is essential to integrate adaptation into different public policies (even though they are adaptation measures *stricto sensu* and coordination tasks that need to be funded).

4. Implementation steps of an adaptation strategy

Many measures exist to adapt or help adapt to climate change. However, all adaptation measures are not desirable and some probably cost more than the value of the impacts that they can avoid. Moreover, among the effective and cost-effective measures, some will be necessary and urgent, whereas others will only be implemented in several decades. It is therefore important to have a methodology to define an adaptation strategy that is both coherent and effective. Several approaches are possible, depending on the initial situation and the means available. **This report proposes a methodology that is obviously not the only one possible.**

The methodology proposed is based on the main idea that adaptation is a dynamic process and that, as a result, we must design a strategy for only several years, but one that takes the long-term into account and that can be readjusted throughout the century as new information becomes available. Within this framework, in addition to determining what must be done, we must, above all, determine *when* it must be done, taking possible time arbitrages into account, and *who* is responsible for doing it.

The methodology proposed here to build an adaptation strategy includes seven steps, to be applied at the same time to each of the sectors concerned, and then globally:

Step No.1: Construction of climatic and economic scenarios on which the work will be based (see Section 5.2), and identification of the impacts of climate change and possible adaptation measures. The basic material on which public decision-makers will base their decisions is precisely a collection of possible adaptation measures, proposed by different stakeholders and different institutions [(21)]. The definition of a plan must therefore begin by ensuring that this basic material does not contain a major omission, i.e., that the major impacts, the major economic sectors, all of the territories and all of the social categories are well represented, and then by determining which measures have priority.

Step No.2: Screening of identified adaptation measures, taking into account the urgency of their implementation. It is useless to include all of the adaptation measures in a first plan. Some measures or investments can wait decades. **The selection of measures depends both on the dynamics of climate change impacts and the dynamics of the concerned economic sectors.** For all practical purposes, priority measures are those that aim at reducing impacts that are, in decreasing order of importance:

- going to occur in the near future (see Box n°3), or can that already be observed (e.g., the increase in the frequency of heat waves);
- going to occur in a distant future or that are limited to extreme warming conditions, but that are well established scientifically and for which adaptation strategies will only have an effect on the very long-term (e.g., a limited rise (< 1 m) in sea level and land-use plan);
- going to occur in a distant future or that are limited to extreme warming conditions and that are highly uncertain, but with potentially serious consequences and for which adaptation strategies will only have an effect on the very long-term (e.g., major rise (> 1 m) in sea level).

Step No.3: For each impact, different possible adaptation measures must be identified and then **evaluated by a relatively simple multicriteria analysis of their costs and benefits.** This evaluation can be done by using quantitative models or methods when possible, or from qualitative analyses or experts' opinions when models are not available (which is often the case). This analysis must satisfy several criteria:

- **The analysis must not just integrate the monetary market costs, but must also take the many different dimensions of costs and benefits into account [(22)]:** impacts on the quality of life, impacts on health, impacts on biodiversity, impacts on inequalities and the distribution of wealth, individual and social security, etc. It is particularly important to determine who would pay for a measure and which financing sources should be considered, as well as to ascertain who would directly profit from the benefits of the measure. Each measure can in fact lead to redistribution effects, with winners and losers. **The geographic and temporal distribution of costs and benefits must be considered.** It is particularly important to determine when the costs of the measure will come to bear (initial investment vs. annual cost) and at what point in time the benefits will appear.
- **The analysis must take in into account synergies (and conflicts) with other policy objectives and sectorial policies.** For example, the use of air-conditioning is often in contradiction with policy objectives in terms of energy consumption and greenhouse gas emission reductions; the modification of a building can be oppose for patrimonial

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[21] The French case is interesting in this respect because the first stage of the construction of the National Adaptation plan is precisely a broad consensus-building phase with the different socio-economic stakeholders that aims at identifying an initial and very wide-ranging list of possible adaptation measures.

[22] A more in-depth discussion of these aspects can be found in Hallegatte et al. (2011).

and cultural reasons (preservation of cultural and historical heritage). In contrast, the implementation of more restrictive land-use plans is often synergistic with natural risk reduction. These oppositions or synergies can sometimes be expressed as costs or monetary co-benefits (e.g., for energy consumption), but this is not always the case (e.g., heritage preservation). **As a first step, it is possible to look for "no regret" measures for which the co-benefits alone justify the implementation of the measure.**

- **The analysis must assess the robustness to uncertainty:** first, obviously, in terms of climate uncertainty (is it doable to implement a measure that provides benefits for all possible future climates?), as well as in terms of uncertainty on socio-economic developments (e.g., in relation to the geographic distribution of the population within a national territory or to the existence of new technologies to save water). **We will first look for robust measures (which are beneficiary in all of the cases) or flexible (that can be adjusted in view of new information in the next decades)** (Hallegatte, 2009)**.**

<u>**Step No.4**</u>**:** The preceding step must identify a relatively reduced set of promising measures. **More in-depth studies – i.e., more time-consuming and work-intensive – could then be carried out.** This is especially the case for cost-benefit analyses. These analyses should not neglect the points mentioned in Step 3, and particularly the uncertainty about climate change and socio-economic trends and redistribution effects (in terms of time, geography and sociology), as well as the coherence with other objectives or sectorial policies. This type of analysis is a complement to (but does not replace) the multicriteria studies mentioned above because it provides a much finer analysis of the effects of time and specific arbitrations between different alternative solutions.

<u>**Step No.5**</u>**: Measures will be selected on the basis of the results of different analyses – particularly multicriteria and cost-benefit – and the resources that are available.** Particular attention must be given to the coherence between different measures of an adaptation strategy and the consistency with other sectorial policies. For example, responses to climate change in terms of electricity production (cooling of thermal and hydroelectric power plants), irrigated agriculture, and protection of the biodiversity of river ecosystems cannot be designed independently of each other because the volume of water available must be shared between these uses and must allow the implementation of each of these responses. Therefore, trade-offs between adaptation measures (and, thus, between sectors) will be necessary. Consistency with other sectorial policies is also crucial. For example, adaptation of agriculture to climate change must take other policy objectives into account (income support for farmers, reduction of pesticide use, etc.) It will therefore be necessary to look for synergies and to identify conflicts. Once again, it will be necessary to arbitrate between existing policy objectives and adaptation to climate change.

<u>**Step No.6**</u>**: For each of the measures selected, an adaptation plan must include indicators of the effectiveness of the measure, as well as a time horizon for which effects must be visible on the indicators.** For example, in the case of a modification of a land-use policy, the number of new buildings built in a flood-prone area can be monitored and its reduction measured and controlled to ensure that the measure achieves its goal. It should be mentioned that the indicator is not necessarily the level of climate damage itself. Therefore, for a land-use policy, the number of buildings in a flood-prone area is indicative of the success of a policy before a drop in economic losses linked to flooding can be measured. Considering the time horizons of various measures, an adaptation strategy must include its assessment and adjustment possibilities.

<u>**Step No.7**</u>**: The effectiveness of the adaptation strategy must be evaluated** and adjusted in relation to: (1) the results of preceding measures, using indicators defined when the measures were implemented; (2) new scientific information about climate change; (3) socio-economic and

technological changes that could have taken place. This is done by going through the same process, beginning with Step 1. Even if monitoring is continuous, a complete revision can take place on a regular basis. This should probably be done between five and ten years after the initial implementation of the strategy.

Questions linked to the operational implementation of such a process, especially related institutional and legal questions, require a detailed analysis. This analysis should be specific to each country, to take into account local contexts and pre-existing governance habits, and is not in the scope of this report.

Box n°3: Forecasting climate change for the near future (2010-2030)

It would be extremely useful to be able to forecast climate change over the next two decades in order to implement adaptation plans. However, climate change is relatively limited at these time scales, and climate variability is such that the climate signal is not dominant. Consequently, climate models, which only reproduce natural variability at the statistical level, are incapable of predicting changes in the near future. It is therefore essential not to over-interpret the results of these models and not to use their output as forecasts, without taking into account natural variability.

The inability of models to predict climate changes in the next two decades could change if work on the ten-year forecast – a focus of research today – progresses. This would nevertheless require considerable strides in numeric modeling and better knowledge of ocean conditions that determine climate change on these time scales. Improved knowledge requires more developed measurement networks in oceans worldwide.

5. The use of economic instruments in the development of an adaptation strategy

In the methodology proposed in the preceding section, economic assessment of adaptation measures plays an important role. This section therefore focuses on the question of assessment, i.e., on Steps 3 and 4, to propose approaches that would allow us to take into consideration the specificities of adaptation described in Section 1.2, and primarily, uncertainty, dynamics, inertia and possibilities of economic bifurcations and transitions.

Cost-benefit analysis of adaptation measures is made difficult by the uncertainty on the impacts of climate change and therefore on the benefits of adaptation measures. In presence of uncertainty, several assessment methods are available, depending on the type of information we have on climate scenarios and on the type of hypotheses that we would like to formulate (or not) on their probabilities of occurrence (Section 5.1). In all of these methods, the choice of climate scenarios is a key element. In Section 5.2, we therefore propose elements that will allow us to choose the scenarios to be considered. **Nevertheless, we believe that, despite uncertainty, cost-benefit analysis (public or private) is the method of reference, provided that sufficient information is available.** The way in which this method can be applied to the assessment of adaptation policies is discussed in Section 5.3.

5.1. Comparing adaptation methods in the presence of uncertainties

Following is the description of four methods that allow us to compare adaptation measures within a context of uncertainty about the future climate.

The first method is cost-benefit analysis with uncertainty: In this case, we are dealing with uncertainty in relation to climate scenarios by attributing subjective occurrence probabilities to them (i.e., based on beliefs determined from actual knowledge rather than occurrence frequencies). The "best" project will then be the one that maximizes the expected net present value (i.e., the average of the costs and benefits weighted by the occurrence probabilities for every possible states of the world) [(23)]. When the necessary information is available, cost-benefit analysis is particularly useful because it makes it possible to evaluate policies in all possible cases, as well as enabling a fine trade-off between measures, for example, when there are different consequences in terms of time or space distribution of costs and benefits. Even when all of the information necessary for the calculation is not available, a sensitivity analysis often makes it possible to reveal trade-offs that are not necessarily obvious beforehand. We will come back to the use of cost-benefit analysis to assess adaptation policies in Section 5.3.

A criticism often made of cost-benefit analysis with uncertainty is the little importance it attributes to low-probability high-impact scenarios, while policies are often specifically implemented to avoid these scenarios. To avoid this problem, we can use "risk management" models whose principle is to limit the probability that losses reach a critical level. In practice, we look for an adaptation policy in which scenarios with losses exceeding 1% of the GDP will have a cumulative occurrence probability of less than one in a thousand [(24)]. The hazard threshold retained (1% of the GDP in this case) and the cumulated occurrence probability (one in a thousand here) are subjective and have to be determined through a political process.

An extension of the preceding method is sequential analysis (e.g., Ambrosi et al., 2003) that aims at minimizing the cost of maintaining the possibility of reaching a given target despite uncertainty over a period in the near future (e.g., 2010-2020). In the case of a rise in sea level, for example, we can assume beforehand that there are three possibilities (20 cm, 80 cm, 140 cm), and that we will know which of these three values is correct in 2020. After 2020, we can therefore implement an optimal policy in relation to the true value thanks to a cost-benefit analysis within a context of certainty. Between 2010 and 2020, within a context of uncertainly, we apply a strategy aimed at minimizing the "cost of the error". This cost is expressed in the value of buildings that eventually have to be abandoned if predictions of the rise in sea level were too optimistic at the building stage, and in loss of construction opportunities if predictions were too pessimistic (and therefore leading to too restrictive measures) [(25)].

Nevertheless, these three methods require subjective occurrence probabilities for each climate scenarios. However, it is often difficult to determine these probabilities in the case of climate change. In practice, we often only have a set of possible scenarios to work with. In this case, we can use a scenario-by-scenario decision approach (see, e.g., Lempert and Schlesinger, 2000), and look for policies that are acceptable within a maximum number of scenarios. We therefore no longer attempt to maximize the benefits within a given scenario (or within the average of a set of scenarios) but, instead, to remain above the acceptable level of benefits for the set of scenarios (or for as many scenarios as possible). The most rigorous version of this method, in which we try to remain above an acceptable level for all of the scenarios, is similar to what is referred to as the "**maximin approach"**, in which we simply attempt to optimize the most pessimistic scenario. The disadvantage of this approach is that the set of strategies is determined on the basis of the most pessimistic hypothesis that is generally

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[23] To take risk aversion into account, we can also work in expected utility rather than in monetary costs and benefits, making it possible to consider basic needs and the asymmetry between profits and losses.
[24] In the same way, we can establish a policy so that the worst-case scenarios with a probability of 1 in a thousand lead to losses of less than 1% of the GDP.
[25] This method is based on the concepts of option value and quasi-option value (Henry, 1974; Arrow and Fisher, 1974), as well as on the information value, and explicitly takes into account the possibility of delaying decision-making to avoid becoming involved in a strategy that would be vulnerable to new information. It also encourages the choice of robust, flexible and reversible strategies that are capable of adjusting themselves to new data.

highly unlikely. We therefore focus all of our attention on extreme scenarios and give no credence to the most likely scenarios. In the most flexible versions of the approach, we simply attempt to limit the number of scenarios in which results are considered as unacceptable, where "unacceptable" is obviously defined by a political process. This approach therefore aims at implementing measures that are sufficiently effective within all the scenarios, i.e., uncertainty-robust measures or measures that can be adjusted when new information becomes available, e.g., flexible or reversible measures (see Hallegatte, 2009, for an application to adaptation to climate change).

Two remarks should be made in conclusion to this section. First, no method is perfect. The different methods proposed here can be used depending on the information available about occurrence probabilities and depending on policy choices, particularly on the importance given to extreme scenarios. The differences between the methods proposed are not as great as they may appear at first glance. In fact, subjective probabilities can be chosen to reflect strict preferences in relation to extreme scenarios.

In contrast, a scenario-by-scenario decision approach has the disadvantage of making the comparison between protection costs and expected benefits implicit, a comparison that is central to the discussion on public policies. **It therefore appears preferable, whenever possible, to use a cost-benefit analysis with at least two "optimistic" and "pessimistic" scenarios (see Section 5.2) to which we attribute subjective occurrence probabilities, being careful (i) to examine the robustness of results to difference choices of probabilities, and (ii) to specify as a constraint, the non-realization of some states of the world considered to be unacceptable.** This type of analysis actually makes it possible to explore, to the greatest extent possible, the realm of possibilities, to identify eventual breaking points, and to test the consistency of beliefs about climate change and the level of action.

Within this context of radical uncertainty, **cost-benefit analysis, like the other methods presented in this section, would only be able to provide a response contingent on a set of beliefs about the future and an attitude in relation to risk, rather than "the" good response to the level of adaptation.** In conclusion, the decision is political and the role of the analysis is to shed light on it. In this respect, an essential criterion for choosing between the methods presented here is that **the method chosen must be the most apt, under the current circumstances, to be "language of and issue of negotiation" between decision-makers** (in the words of Claude Henry, 1984). The transparency of the hypotheses and the clarity of the calculation are absolutely essential to the analysis in this case.

5.2. Choosing climate scenarios

In all the methods described above, it is necessary to evaluate the costs and benefits of adaptation measures within **several** climate scenarios. In fact, **the choice of adaptation measures depends, to a large extent, on the choice of climate scenarios.** For example (see Hallegatte et al., 2007a), the installation of air-conditioning in a certain number of sensitive places (retirement homes, hospitals, housing for the elderly, etc.) may be sufficient to adapt to limited climate change, and it would thus be useless to change building standards. On the other hand, in the event of larger climate change, a generalization of air-conditioning or structural modification is indispensable, and it would therefore be desirable to change building standards for new structures as of today. The question of the scenario selection is therefore extremely important. **Designing an adaptation strategy on the basis of a single climate scenario could lead to major maladaptation and could be worse than no action at all. It is for this reason that the methodology proposed in Section 4 begins with the selection of climate and economic scenarios.**

In the absence of mitigation policy, IPCC models project an increase of average annual temperatures from 2 to 6°C worldwide between now and 2100. **This range includes the**

uncertainty related to the greenhouse gas emissions scenario and the uncertainty related to the response of the climate to a given concentration of greenhouse gases. This range is reduced in presence of climate policies. Its upper level, in particular, decreases. However, it is difficult to determine the scope of future climate policies at this time, and the announced international objective of limiting warming to 2°C cannot be considered as a certainty. As for the rise in sea level, uncertainty is even greater, with scientific publications projecting a rise of between 20 cm and 1.5 m, depending on the case. Finally, for shorter time spans (2010-2030), it is of utmost importance to take natural variability into account since it can significantly modify climate changes and obscure or magnify overall climate change (see Box n°3).

In this uncertain situation, it is reasonable to use several scenarios and to ensure that the measures implemented are either robust in terms of this uncertainty or can be adjusted as new information becomes available. Concerning the choice of scenarios, we propose:

- **An optimistic scenario**, assuming ambitious climate policies at the international level (comparable to an SRES/B1 scenario) and a low-level climate response to greenhouse gases.
- **A pessimistic scenario**, assuming the absence of ambitious measures to limit global warming (comparable to an SRES/A1 or A2 scenario), and a strong climate response.

On this basis, precipitation and the geographical structure of climate change can be extracted from climate model output. A high degree of uncertainty exists in relation to the local expression of climate change, and different models lead to very different regional patterns. In theory, it would be necessary to use as many models as possible to carry out this work. In practice, we can use the most contrasted models.

As explained in Section 4, **in the case of very big impacts and long adaptation times (for example, the loss of a highly urbanized area due to the rise in sea levels), it is reasonable to take the most pessimistic scenarios into account, even if their probability is very low** [(26)], whereas for more limited impacts, we can take only the most likely scenarios into account.

We can compare this approach to that of insurance for risk-averse stakeholders: for very serious events (house fires or disability), we are ready to pay for insurance, even if the probability of occurrence is low (because the aversion to the risk is such that the loss of utility increases non-linearly with the loss); for less serious events, insurance may no longer be justified if the probability is too low because we are capable of dealing with the event should it occur. Therefore, **the choice of an extremely pessimistic scenario can be justified if the potential consequences are very serious.** When developing an adaptation plan, we can therefore sometimes choose to use the most pessimistic hypotheses in the case of particularly vulnerable sectors.

5.3. Application of cost-benefit analysis to the assessment of adaptation policies

Cost-benefit analysis (private or public, depending on the case) is a very powerful tool for assessing adaptation policies. This method - commonly used to analyze public policies – is general and can be applied to all types of private and public investments. A complete description of the method is well beyond the scope of this paper. However, the interested reader will find detailed information about the method and its most recent developments elsewhere. **We are interested here in the way in which this method can be used to evaluate adaptation projects** and, in particular, investment projects concerning long-term capital.

[26] This approach is similar to "hazard management" used, for example, for the dangerousness of chemical products.

The purpose of cost-benefit analysis is to compare projects or policies among themselves in order to determine which one will provide the greatest net benefit for the individual conducting the analysis (private cost-benefit analysis) or for society at large (public cost-benefit analysis).

The cost-benefit analysis approach (private as well as public) is simple: (i) identify competing projects; (ii) identify sources of uncertainty and future possible states of the world; (iii) evaluate the costs and benefits for each project, in all possible states of the world; (iv) calculate the present value of costs and benefits; (v) calculate the expected net present value of different competing projects (if we have or can estimate the occurrence probabilities of states of the world); and (vi) evaluate the robustness of the result, including in relation to hypotheses on probabilities.

Identification of competing projects in the case of adaptation raises no specific problem. In contrast, it is important to realize that **the initial (current) situation is not necessarily optimal in relation to current climate risks.** It is therefore essential to define the reference situation in relation to which the measures are evaluated so that the figures provided have a meaning (see Box n°4). In the case of protection projects concerning natural risks, it is, in fact, common that the protection levels observed in the field are not the result of a specific risk analysis and an explicit policy choice but, instead, are the result of an empirical historical process. In reality, "constant risk level" adaptation projects (i.e., reasoning in terms of efficiency costs rather than benefit costs) generally do not lead to optimal adaptation in relation to climate change.

The specificity of adaptation projects is that their assessment must take the risks linked to climate change impacts into account (limiting risks is the rationale for these projects). As we emphasized above, uncertainty about climate change impacts is particularly important, and even more so at the level of small geographic scales. On the one hand, it is difficult to list all of the possible states of the world. On the other, it is not possible to link objective occurrence probabilities to these states – for instance because their occurrence is partially dependent on future mitigation actions.

Once the different climate scenarios are established, identification and evaluation of the costs and benefits of adaptation measures does not necessarily present any particular difficulties. However, two important points must be stressed. **First, even for a given climate scenario, the impacts and, therefore, the costs and benefits of adaptation measures can be uncertain.** For example, the response of forest ecosystems to climate change is widely unknown. **Second, climate shocks often have significant indirect effects** (for example, the effect of the degradation of an infrastructure on the rest of the economy, etc.) (see, e.g., Hallegatte et al., 2007b; Hallegatte, 2008).

In addition, climate change adaptation measures can have significant co-benefits or co-costs. For example, a modification of building norms can lead to an improvement in the comfort of housing units, in addition to making them more effectively adapted to climate change. We can even imagine that investments made within the framework of an adaptation plan could provide a solution to certain pre-existing problems. **These co-benefits and co-costs should be taken into account in the analysis.**

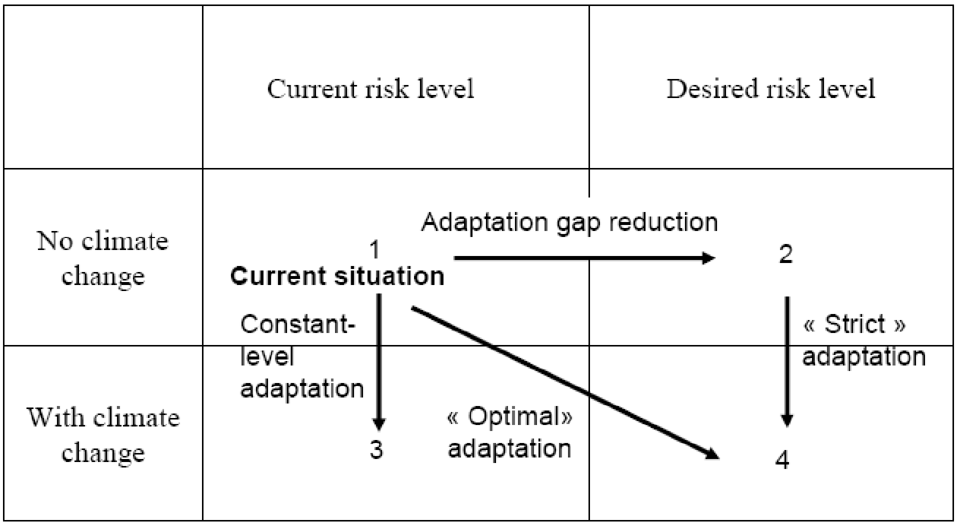
By way of construction, most of the adaptation questions that arise today – and that may therefore be analyzed from a cost-benefit point of view – deal with choices whose consequences have very long-term implications (at least several decades). To assess these projects, as in the case of the assessment of mitigation projects, the discount rate adopted is therefore an important element in the analysis. This is neither the time nor place to discuss the discount rate. In any case, discount rates for public projects are often set by the government (the Green Book in the United Kingdom, the report of the French Planning Office in France (Lebègue, 2005), of the Office of Management and Budget circulars in the USA). Moreover, the discount rate often has less impact on the final result than uncertainty on the impacts of climate change (Lecocq and Hourcade, 2004) and, therefore, on the benefits of adaptation measures.

Box n°4: Different definitions of adaptation cost

When analyzing adaptation, it is important not to assume that the current situation is optimal. It is in fact common that observed protection levels are not the result of a specific risk analysis and an explicit policy choice. Instead, they are often the result of an empirical historical risk management process. We can therefore observe situations in which the existing natural risk level is too high, compared to the level that would be considered ideal if a risk analysis was actually conducted, or too low, i.e., with protection costs that are too high in relation to the optimal level.

Adaptation strategies are very different depending on whether they begin with an ideal situation where the flood risk level is at its optimal value, or a sub-optimal situation. This difference is illustrated in the table below. The real situation today is that of square 1, a situation where the risk is not necessarily at its optimal value. Different definitions of adaptation are represented in the table below, which is interpreted as follows:

- The passage from square 1 to square 2 is the reduction of the "adaptation gap", i.e., the passage from a sub-optimal situation to a situation that would be optimal in the absence of climate change.
- The passage from square 2 to square 4 is adaptation in the strict sense, i.e. the investment necessary because of climate change alone, to go from an optimal state without climate change to a new optimal state with climate change. This type of adaptation can be qualified as " adaptation *stricto sensu*" and corresponds to actions that would not be desirable without climate change and that only become desirable because there is a change in climate.
- The direct passage from square 1 to square 4 is the trajectory that should be followed in practice, i.e., passage from the current sub-optimal situation without climate change to an optimal situation with climate change. This adaptation can be qualified as "optimal adaptation".
- Finally, the passage from square 1 to square 3, i.e., maintaining the risk at its initial level, can be qualified as "constant level adaptation". This type of constant level adaptation is often that which is analyzed in the scientific literature when authors begin with the premise that the current situation is optimal.



When climate scenarios and their subjective occurrence probabilities have been determined, when the costs and benefits of adaptation measures have been estimated, and when the discount rate has been chosen, obtaining the net present value of competing projects is only a question of calculation. On the other hand, as we have already mentioned above, **a sensitivity analysis is absolutely necessary for the cost-benefit analysis results to have a meaning.** Many methods are available to carry out this assessment, from the simple variation of a parameter – all the others being constant – to complex numerical methods such as the Monte Carlo method. Once again, the important point here is that the cost-benefit analysis (or any of the other methods described above) cannot claim to provide "the" best adaptation project but can, instead, lay out the conditions (including beliefs about climate change) under which one or another of the projects is preferable.

6. Summary

Adaptation has long been neglected in the debate and policies surrounding climate change. However, increasing awareness of climate change has led many stakeholders to look for the best way to limit its consequences and has resulted in a large number of initiatives related to adaptation, particularly at the local level. Adaptation has also become increasingly important in international negotiations.

Adaptation can be defined as *the set of organization, localization and technical changes that societies will have to implement to limit the negative effects of climate change and to maximize the beneficial ones.* This definition encompasses extremely varied types of actions that can be applied to a wide range of sectors. Issues differ depending on geographic scales, zones and contexts, and its implementation involves a combination of widely diversified instruments.

This paper proposes a general economic framework to help stakeholders in both the public and private sectors to develop effective adaptation strategies. To do this, it lays out the general issues involved in adaptation, identifies relevant public action levers and then describes their implications for the design of adaptation strategies.

Four major issues for adaptation strategies

To begin with, uncertainty on future climate needs to be taken into account. In fact, types of uncertainties with cumulative effects have to be considered: those related to the future evolution of the climate at global scale – expected impacts of climate change are not comparable depending on whether we choose a scenario with an average temperature increase of +2°C or one of +4°C; those related to the climate change scenario at the local level; and those related to future changes in the adaptation capacities of our societies. Uncertainty makes it necessary to assess adaptation measures in view of their degree of flexibility, i.e. their capacity to be adjusted if and when new information becomes available.

Secondly, given the degree of technical, economic, political, institutional and cultural inertia, it is not always possible to take totally flexible adaptation measures. For example, the asset lifespan in sectors such as infrastructure, building or forestry is of the same order of magnitude as the climate change time scale itself. In these cases, it is necessary to make adaptation choices without having complete information, despite the risk of "maladaptation" *ex post*.

Thirdly, climate change is a continuous process. As a result, the issue is not how to adapt to a "new" climate, but how and at what price we can adapt our societies to a "constantly evolving" climate. Adaptation must therefore be understood as a permanent transition policy on the very long-term. An adaptation plan for several years is only a stage in this process.

Finally, in some cases it is too costly or technically impossible to adapt "at the margin" while maintaining the same activities and existing services in the same place. Adapting to climate change may require bifurcations towards other activities and/or other locations, making it necessary for adaptation policies to be developed and applied within an intersectoral and systemic framework. This also implies that the future impacts of climate change should be immediately integrated into land-use planning choices and urbanization plans. The question of transitions between activities and/or between regions then becomes a central issue.

The role of public policy in adaptation

The legitimacy of public action in terms of adaptation is not obvious because the benefits of adaptation measures are generally private, inciting households, businesses and communities to act spontaneously. However, circumstances may exist in which this spontaneous adaptation runs the risk of being insufficient or even counter-productive. Reflection is necessary on a case-by-case basis to determine the areas in which intervention by public authorities is necessary. This paper identifies four of them.

First, public authorities have a key role to play in the production and dissemination of information on climate change and its impacts and on ways to adapt to it in order to allow private stakeholders to make intelligent, well thought-out decisions. Transmitting information on uncertainty and on tools with which to analyze it is essential in this case.

A second type of public action aims at adapting standards, regulations and tax measures. This paper takes the example of standards that affect water demand and those that relate to long-term fixed capital (e.g., building and infrastructure). In addition to technical standards *stricto sensu*, it may also be necessary to adapt procedural standards as well as other norms and standards not directly linked to the climate but that have an impact on adaptability (e.g., in the financial domain).

The third type of public action concerns institutions. By rapidly and unpredictably modifying circumstances, climate change will lead to increasing tension for institutions and existing contracts. We must be sure that concerned institutions are capable of identifying the signals that precede tensions and crises, of balancing the interests of the different parties involved, and of effectively implementing the solutions that they propose. History suggests that institutions play a major role in adaptation. For example, Holland's success with flood management is as much due to the establishment of the institutions necessary for risk management as for its technical ability to build seawalls.

The fourth type of public action deals with direct adaptation actions of governments and local communities in terms of public infrastructure, public buildings and ecosystems under the responsibility of government agencies, e.g., state parks and state and communal forests. More generally speaking, it is necessary to integrate the future impacts of climate change into land-use policies and major investments that influence land-use.

Methods to be used to build a public adaptation strategy

A seven-stage process to build an adaptation strategy is described in this paper. It begins with a broad identification of the most urgent measures, particularly those resulting from imminent impacts or concerning choices to be made today but that will have very long-term consequences. This first screening based on urgency identifies what is most important and simplifies the building of an adaptation strategy.

An adaptation strategy can then be built on this basis, especially by looking for robust and flexible measures that are able to cope with the uncertainty in future climates and to maximize the adaptation co-benefits. Measures whose co-benefits are greater than their cost, often qualified as "no-regret", are of particular interest in this case. To build a long-term adaptation strategy, it is also necessary to build the indicators that will make it possible to assess the effectiveness of the measures, to allow for corrections and adjustments in following years.

Provided that uncertainty is satisfactorily integrated, cost-benefit analysis is an effective tool for assessing the economic opportunity of the adaptation measures considered. However, other approaches and multicriteria analyses, in particular, are also essential to make the best possible individual and collective choices concerning adaptation, taking into account the complexity of the consequences of climate change and adaptation actions.

7. Recommendations

The following three important messages could be drawn upon completion of this paper. They served as a basis to establish a series of recommendations.

- The first message concerns the legitimacy of public action in relation to adaptation, which is not automatic since most adaptation actions generate private benefits. A reflection is therefore necessary on a case-by-case basis to determine the areas in which the intervention of public authorities is required or relevant.
- The second message is that direct action on public assets, perhaps the most visible, is only one of the public action components in relation to adaptation. The primary responsibility of public authorities in this area is to provide a favorable adaptation framework for private stakeholders, particularly through actions in terms of the production and dissemination of information, standards, regulations, taxation and institutions.
- The third message deals with the role of economic analysis in the decision-making process. Provided that uncertainty is correctly integrated, cost-benefit analysis is an invaluable tool for assessing climate change adaptation policies. This tool is capable of reducing the range of relevant measures in a given situation, while it is generally unable to identify "the" good measure. Group arbitration is therefore most often necessary to make a decision.

To give a more tangible meaning to these general messages, the following recommendations were drawn up:

- Governments and international institutions have a key role to play in the production and dissemination of information necessary to promote adaptation by all of the economic stakeholders. In particular, we must ensure that uncertainty is properly taken into account in order to avoid mistakes that could lead to a maladaptation that could be worse than no action at all.
- Specific investments will be necessary for successful adaptation. However, we must remember the importance of "soft" actions that have an impact on information, standards, regulations and institutions. These generally low-cost measures can generate considerable benefits and are an indispensable addition to investment policies.
- Without privileging a specific approach, we must not concentrate on adjustments at the margin of existing economic structures without evaluating the possibilities of larger economic bifurcations or transitions. This is especially the case in regions that depend on an activity that is highly vulnerable to climate change.
- The importance of the challenges inherent in sectorial and spatial bifurcations (migrations of populations and capital) requires the creation of coordination tools to improve the way we conceive of adaptation policies related to a given territory in an integrated way, and to avoid inconsistencies and conflicts.
- An adaptation plan must focus on urgent needs and not attempt to adapt societies to all of the impacts of the next 100 years. Identification of priority actions is crucial. Very long-term impacts should be taken into account when they require actions whose

effectiveness is only real on a very long-term basis (e.g., urbanism and land-use plans). Low-probability scenarios should be taken into when their potential impact is very large (e.g., possibility of large sea level rise); when impacts are more limited, it is possible to focus only on the most likely scenarios.

- Regular review mechanisms are necessary to take new scientific information into account and consequently adjust measures. To do this, the development of a performance indicator for adaptation actions is important.
- Adaptation must take synergies and conflicts with other policy objectives into account, and particularly mitigation policies for climate change and protection of biodiversity.

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