Chapter 2
Background on Uncertainty Assessment Supporting Climate Adaptation Decision-Making

Leendert van Bree and Jeroen van der Sluijs

Key Messages

- Analysing, characterising, and dealing with uncertainty forms an integral part of establishing and implementing climate adaptation policy.
- The classical elements used in uncertainty assessment (statistics, scenarios and recognised ignorance) can be expanded toward five principal uncertainty dimensions that are crucial for informing/supporting adaptation decision-making: location, level, nature, qualification of knowledge base, and value-ladenness.
- In practice, to deal with uncertainties, but also because of time and budget constraints, uncertainty assessments may follow a three step approach: (1) identify and characterise sources of uncertainty; (2) weigh, appraise, and prioritise uncertainties; and (3) select and apply methods for dealing with uncertainties in decision-making and policy.
- Based on political and societal preferences, adaptation strategies could either use top-down or bottom-up approaches considering adaptation actions based on the best prediction, robustness, or resilience.

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(continued)

- Adaptation policies that focus on enhancing the system's and society's capability of dealing with possible future changes, uncertainties and surprises (e.g. through resilience, flexibility, and adaptive capacity) seem most appropriate.
- For potential climate-related effects for which rough risk estimates are available, 'robust' measures are recommended.
- For potential climate effects with limited societal and/or political relevance, 'no-regret' measures are recommended.
- For highly relevant potential climate-related effects, precautionary measures can be considered.

2.1 Introduction

Climate affects societies in many ways, and climate variability and climate change are important factors for societal development (Fig. 2.1). Over the past century (1906–2005), global average surface temperatures have increased by 0.74 ± 0.18 °C (IPCC 2007a). Based on observations of global air and ocean temperatures and changes in snow/ice extent and sea level, the Intergovernmental Panel on Climate Change (IPCC) concluded that it is 'unequivocal' that the climate system has warmed (IPCC 2007a).

According to the IPCC, most of the warming since the middle of the twentieth century is *very likely* to be due to the human-induced increase of atmospheric greenhouse gas concentrations. Various climate impacts on both physical and biological systems have been observed. IPCC temperature projections for the end of the twenty-first century range from an increase of 1.1–6.4 °C, compared to end of the twentieth century. These changes in the global average temperature have a wide variety of global, regional and local effects, such as changes in: temperature, sea levels, precipitation and river runoff, drought, wind patterns, food production, ecosystem health, species distributions and phenology, and human health (IPCC 2007b; EEA 2012, 2012a).

At the regional level, changes can, however, substantially differ. For example, the observed Western European increasing temperature trend over the past decades is much larger than the global average trend. Regional climate effects such as changes in atmospheric circulation, and environmental changes such as lower aerosol concentrations, are believed to have played a role in this difference (e.g. PBL 2009). The impacts of expected global changes will differ by region and sometimes by season. In many cases, the impacts will be detrimental, although some regions might welcome some of the changes, provided they remain relatively small; for example, in cold-limited regions warming could be useful for agriculture or access to mineral reserves.

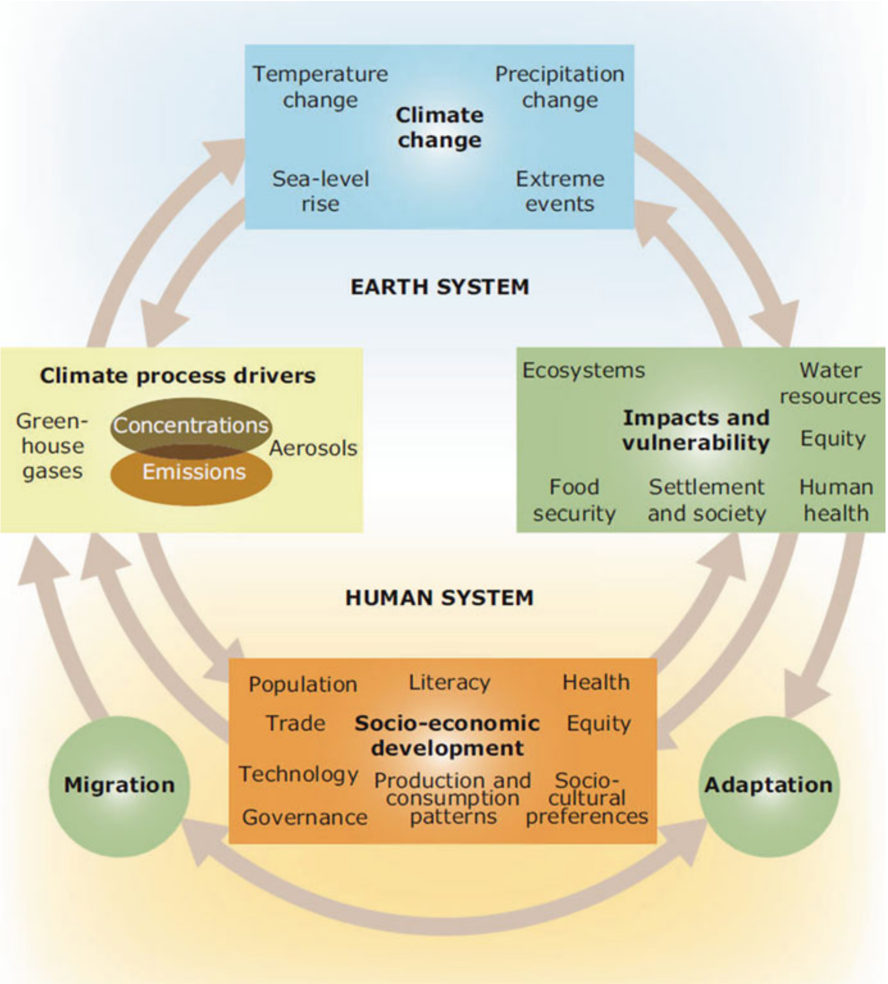

Fig. 2.1 Schematic framework representing anthropogenic climate change drivers, impacts and responses, and their links (EEA 2012a)

Two main responses have emerged in recent decades to deal with climate change: mitigation and adaptation. Mitigation is generally described as "*Limiting climate change by reducing greenhouse gases (GHG) emissions and enhancing sinks*". Adaptation has been described in various ways (Willows and Connell 2003; IPCC 2007b), but they all come down the central issue of "*Adjustments in ecological, social, or economic systems in response to actual or expected climatic stimuli and their effects or impacts. It refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change*" (United Nations Framework Convention on Climate Change: http://unfccc.int/focus/adaptation/items/6999.php).

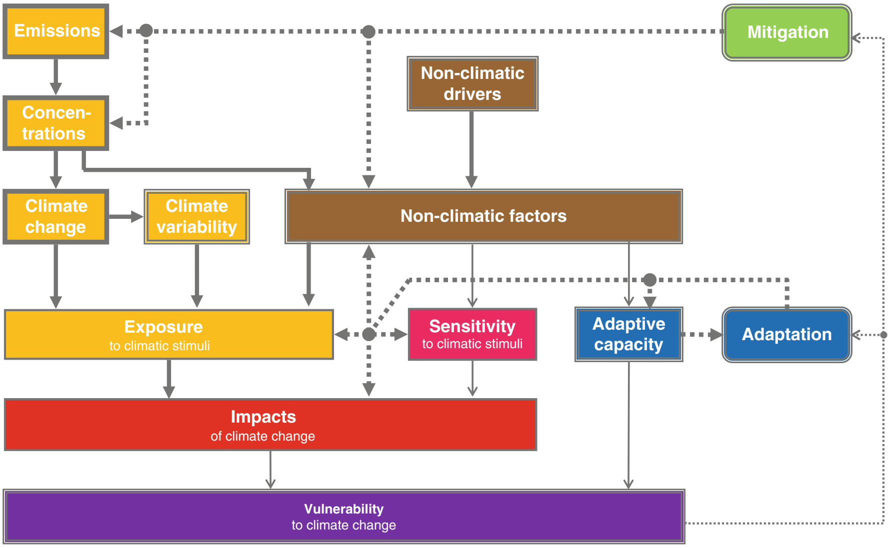

Fig. 2.2 Conceptual framework for climate change impacts, vulnerability, disaster risks and adaptation options (EEA 2012)

Even when taking an optimistic view on the success and timeliness of emission reductions, some degree of climate change is inevitable (e.g. Smith et al. 2000; Dessai and Van der Sluijs 2007; IPCC 2007b), sizeable future emissions will probably remain, and, due to the thermal inertia of the oceans, past emissions have not yet reached their full climate impact.

Adaptation can result in benefits regarding vulnerability to present-day climate and can be economically competitive and attractive. Adaptation measures, however, are seldom taken in response to climate change alone and are often embedded in broader sectorial or integral urban and regional development initiatives (IPCC 2007b; Runhaar et al. 2012). Similarly, in many countries, adaptation strategies address the problem on different spatial scales – that of cities, regions, or on a national scale. They can even be addressed internationally (EEA 2012, 2012a). The adaptation strategies often follow the same format:

- First the reality of climate change is established
- Then there is a scientifically-based analysis of future vulnerabilities and risks on a particular territory (usually based on long-term projections).
- Possible options to counteract these effects are then proposed, and
- Finally these options are assessed in terms of (cost-) effectiveness

This is also reviewed in Chap. 3 for national adaptation strategies.

A widely accepted framework climate adaptation has been developed by EEA (2012) and is presented in Fig. 2.2.

The impacts of climate change are, however, associated with several uncertainties, especially when projections are being made towards the year 2100. These are present in the context of the impact assessment (e.g. in the scenarios and climate data and projections used), and in each step of the assessment itself. They are also cumulative, resulting in an '*uncertainty explosion*' or '*cascade of uncertainty*' (Schneider 1983; Henderson-Sellers 1993; Giorgi 2005; Dessai and Van der Sluijs 2007).

2.1.1 Climate Variability and Climate Change

Whilst the concept of climate change risk is generally acknowledged, there is little apparent distinction made between true (long term) climate change and the short term imperative of responding to climate variability.

The risk is that the "quick-fix", vote-earning, policy responses to climate variability make future adaptation to climate change much harder, less likely, and perhaps even unlikely. For instance, a short-term response to flooding is to provide efficient and effective emergency response and post-disaster support, yet the longer term response should be to reduce the risk through, say, relocation. There has been some policy movement in this direction, for instance managed regression of land on the less populated areas of east coast of the United Kingdom but it has yet to be accomplished within an urban context.

We understand that there is a need for two, yet integrated policy adaptation sets; one for climate variability and one for climate change, which will need different, yet parallel, decision-making processes to be operative. And if possible, there should be clear links between the two. In addition, there is a need for an accurate use of the term "climate change".

To be effective, adaptation should be part of any urban and rural economic development policy and in any related sectorial plans and budgets. We believe that the most important requirements for short-, medium- or long-term decision-making are:

- The policy sets, and
- The projections of climate change risk.

2.1.2 Climate Variability, Climate Change, and Projections of Risks

Climate variability may cause adverse effects like floods, droughts, or intense rainfall/storms. These short-term disruptions could have a significant effect on economies where the economic activity is sensitive to the weather and climate. Policies need to be designed to take sensitivities into account and this is often already the case where they are seamlessly incorporated into a business continuity mind-set of existing governance systems and bureaucracies.

Climate change is on a decadal scale. Very few policies are able to operate on that timescale partly because of the lack of clarity in the objectives and partly because there is a reluctance to commit resources for which there is no political or tangible (near term) return. With these policies the return accrues to a future generation. Individuals are able to plan into the future to a certain extent, by saving a pension for example, but only because they are able to understand the implications of living without a source of income. There is, however, no collective equivalent. An entirely new set of policies must be formulated which have no immediate tangible benefit, being simply a gift to the future.

So, we believe that policies to deal with climate variability and policies to deal with climate change are both needed.

2.1.3 Relationship Between the "Climate" and "Development" Communities

Communities interested in climatic patterns are often distinct from, and do not necessarily "speak the same language" as, those concerned with the economy or resource management. At a minimum, we feel that the understanding between these two constituencies should be improved to establish a common platform for action in areas where the two sets of policy objectives intersect. An example of where progress seems likely is in the factoring in climate change impacts and vulnerabilities when planning for sectoral and overall economic development. Applications range from building institutions for better governance to re-orienting specific investments in physical infrastructure.

How should we enhance climate change adaptation or adaptive capacity through "business as usual" programmes and plans? What are the priorities for investment in adaptation or adaptive capacity, and how should such priorities be determined? These are some of the key questions that need to be answered. Adaptive capacity is the ability to implement adaptations and is a function of such factors as wealth, access to technology, institutional capacity and ability to change.

2.2 Uncertainties in Climate Change

Although trends in climate change are expected to continue, there is considerable uncertainty about the precise rate of change and its concrete impact. Vulnerability to climate change will therefore be greatly affected by the way behavioural, technical, and spatial adaptation strategies and policies are developed and effectively implemented.

A key element in decision-making on climate adaptation is how to deal with uncertainty (Ribeiro et al. 2009). Insight into the uncertainty may determine the preferred adaptation policy in terms of enhancing adaptive capacity, resistance, resilience, robustness or flexibility (Dessai and Van der Sluijs 2007). Models assessing the various sorts of uncertainties to guide policy-makers and decision-makers are therefore crucial instruments for climate proofing (EEA 2012, 2012a).

Decision-making on adaptation under climate uncertainty also involves effective communication and appreciation between science, society, and policy. Such communication and appreciation is often hampered by misunderstandings about the phenomenon of uncertainty in the science and the fundamental limits to climate change and impact predictions.

Lack of systematic attention for unquantifiable uncertainties makes the perceived scientific foundation for climate policies prone to controversies. It can also undermine public support for climate policies, and increase the risk that society is surprised by unanticipated climate changes (Dessai and Van der Sluijs 2007).

The presence of climate uncertainties in adaptation policies challenges all actors in society to assess, evaluate and prioritise adaptation solutions from perspectives such as cost and benefits of investments and short-term and long-term policy preferences. Dealing with complex risks under uncertainty can rarely have a blue-print approach, but does require a tailored and targeted strategy. Because uncertainty assessment is a relatively new scientific discipline, there is significant room for dealing transparently with uncertainty in decision-making and policy. There is also scope for the possible role of other important factors such as ethics (Briggs 2008; Knol et al. 2009).

2.3 Uncertainty Typology

There is a distinction between various sources of uncertainty: decision uncertainty (e.g. related to human decisions that determine future GHG and aerosol particle emissions), natural variability (e.g. related to the internal variability of the climate system), and scientific uncertainty (e.g. related to data gaps, incomplete understanding or insufficient computing power of climate and climate impact models).

An uncertainty typology can be used to classify and report the various dimensions of uncertainty and can improve communication between analysts, policy-makers and stakeholders. It can also help identify where the most (policy) relevant uncertainties can be expected, and how they can be characterised in terms of a number of uncertainty features. Additionally it can serve as a first step of a more elaborate uncertainty assessment, where the extent of uncertainties and their impact on the policy-relevant conclusions are explicitly assessed.

The character of uncertainty is twofold:

- Cognitive – uncertainty in knowledge, and
- Normative – uncertainty in value and goal.

Cognitive uncertainty refers to the level of underpinning and backing of the information (e.g. data, theories, models, methods, argumentation etc.) involved in the assessment of the uncertainty of the problem; it points to the methodological acceptability and the rigour and strength of the employed methods, knowledge and information, and thus it characterises to a certain extent their (un)reliability.

Normative uncertainty relates to the presence of values and biases in the various choices involved e.g. choices concerning the way the scientific questions are framed, data are selected, interpreted and rejected, methodologies and models are devised and used, and explanations and conclusions are formulated etc.

A variety of different types of uncertainty has been defined and used in the literature and in practice. To be pragmatic, in this book we have used an uncertainty characterization originally proposed by Walker et al. (2003) which has been further developed by RIVM/MNP.[1] This three dimension typology, i.e. location, nature and level of uncertainty, can also be expanded to five principal uncertainty dimensions:

- **Location** – the part of the problem in which the uncertainty occurs,
- **Level** – classification on scale from "complete ignorance" to "knowing for certain",
- **Nature** – whether uncertainty is knowledge-based or a direct consequence of inherent variability,
- **Qualification of knowledge base** – evidence and reliability and of information used, and
- **Value-ladenness of choices** – the extent to which choices made in the assessment are subjective.

This classification of uncertainty is quite crucial for a specific uncertain adaptation issue and the choice of transparent and targeted decision-making and policy strategies which try to deal with it. Choices which will be made in the next decades will determine the future level of climate-proofing and the future room for (additional) changes when climate change and its impacts develop at a different rate to that expected. Understanding of these uncertainties will help policy-makers to select appropriate adaptation policies based on societal preferences. We hope this book will help improve climate adaptation decision-making processes and policy-making by analysing, dealing with, and communicating climate uncertainties.

The five uncertainty dimensions are further explained below:

2.3.1 Uncertainty Location

This dimension relates to the part of the problem in which the uncertainty occurs. Five locations can be identified as follows:

- **Context** concerns the scoping and framing of the problem, including deciding what should be inside and outside the system boundaries i.e. delineation of the system and its environment. It also refers to the completeness of the problems involved.

[1] This guidance was developed by the Netherlands Environmental Assessment Agency (formerly RIVM/MNP). More information on it guidance can be found at: http://www.nusap.net/downloads/detailedguidance.pdf

- **Data** refers to measurements, monitoring data, and survey data etc. used in the study. It is the category of information which is directly based on empirical research and data gathering. The data used for calibration of the models involved are also included in this category.
- **Model** concerns the model instruments which are employed for the study. This can encompass a broad spectrum of models, ranging from mental and conceptual models to statistical and causal process models etc. which are often implemented as computer models. In principal models are imperfect and do not take into account all the complexities of the system that is being modelled: model structure (relations), model parameters (process parameters, initial and boundary conditions), model inputs (input data, external driving forces), as well as the technical model, which refers to the implementation in hard and software.
- **Expert judgement** refers to contributions to the assessment not covered above, and that have a more typically qualitative, reflective, and interpretative character. As such this input could also be viewed as part of the 'mental model'.
- **Outputs** from a study are the outcomes, indicators, propositions or statements relating to the problem.

The various aforementioned uncertainties on the location axis can be further characterized in terms of four other uncertainty features/dimensions, which are described in the subsequent sections.

2.3.2 Uncertainty Level

This dimension expresses how a specific uncertainty source can be classified on a gradual scale running from 'knowing for certain' to 'no know'. Use is made of three distinct levels:

- **Statistical uncertainties** are those which can adequately be expressed in statistical or probabilistic terms. For example:
  - statistical expressions for measurement inaccuracies,
  - uncertainties due to sampling effects,
  - uncertainties in model-parameter estimates

  This is often the category of uncertainty referred to in the natural sciences. Scientists may implicitly assume that descriptions of the real system being studied are certain, and that the data employed are representative. However, there may be additional forms of uncertainty at play (see below), which can surpass the statistical uncertainty in size and seriousness and which require attention.
- **Scenario uncertainties** are those which cannot be depicted adequately in terms of chances or probabilities, and can only be specified in terms of (a range of) possible outcomes. For these uncertainties it is impossible to specify a degree of probability or belief, since the mechanisms which lead to the outcome are not sufficiently known. Scenario uncertainties are often construed in terms of 'what-if' statements.

- **Surprise/ignorance uncertainties** are those for which existence is acknowledged, but magnitude cannot be established. There may, for example, be limits of predictability and knowledge ('chaos') or unknown processes. This uncertainty level can appear as recognised ignorance ('known unknowns') or total ignorance ('unknown unknowns').

Uncertainties related to a specific location can appear in any of the abovementioned guises: while some aspects can be adequately expressed in 'statistical terms', other aspects can only be expressed in terms of 'what-if' or 'ignorant' statements.

When we consider climate change, the frequencies distributions in climate data from the past cannot be used for guiding the decisions, because they are likely to change. Consequently we need to address scenario uncertainty and ignorance.

2.3.3 Nature of Uncertainty

Is the uncertainty primarily a consequence of the incompleteness and fallibility of knowledge ('*knowledge-related*' or '*epistemic*' uncertainty) or is it due to the intrinsic indeterminate and/or variable character of the system being studied ('*variability-related*' or '*ontic*' uncertainty)? The first form of uncertainty can possibly, though not necessarily, be reduced by more measurements, better models and/or more knowledge; the second form of uncertainty cannot be addressed this way for example, like inherent indeterminacy and/or unpredictability; randomness, or chaotic behaviour of the climate system.

In many situations uncertainty manifests itself as a mix of both forms; there is an unequivocal delineation between 'epistemic' and 'ontic' uncertainty. Moreover a combination of taste, tradition, specific problem features of interest and the current level of knowledge and ignorance with respect to the specific subject determines to a large part where the dividing line is drawn. The choice can however be decisive for the outcomes and interpretations of the uncertainty assessment; It reflects to a large extent the distinction between uncertainties which are 'reducible' and those which are 'not reducible' by means of further research.

2.3.4 Qualification of the Knowledge Base

The qualification of the knowledge base refers to the degree to which the established results and statements are underpinned (i.e. evidence-based). Examples of such results and statements are as follows:

- The policy-advice statement, such as 'the norm will still be exceeded when the proposed policy measures become effective', or 'the total annual emission of substance A is X kiloton'.
- Statements on the uncertainty in the policy statement such as 'the uncertainty in the total annual emission of substance A is …'

The degree of underpinning can be considered as weak, fair or strong. If underpinning is weak, this indicates that the statement of concern is surrounded by much uncertainty, and deserves further attention.

This dimension in fact characterises the qualification of the knowledge base and the reliability of the information (i.e. data, knowledge, methods, arguments etc.) which is used in the assessment. More detail can be found in the tool-catalogue summarised in Sect. 2.4 and van der Sluijs et al. (2003)

2.3.5 Value-Ladenness of Choices

The final dimension for characterising uncertainties describes whether a substantial amount of 'value-ladenness' and subjectiveness is involved in making the various implicit and explicit choices during an assessment. Examples include:

- How the problem is framed *vis à vis* the various views and perspectives on the problem,
- Which knowledge and information (data, models) is selected and applied,
- How the explanations and conclusions are formed and expressed.

If the 'value-ladenness' is high for any part of the assessment, then it is imperative to analyse whether this could lead to an arbitrariness, ambiguity or uncertainty of the policy relevant conclusions. We believe that different views and perspectives in the assessment should then be explicitly dealt with and the scope and robustness of the conclusions discussed in an explicit manner.

2.4 Methods of Assessing Uncertainty

RIVM/MNP have started to develop a tool catalogue,[2] based on the work of Van der Sluijs et al. (2004). This first tool has provided guidance to the character and extent of different sorts of uncertainties in climate adaptation assessments. Later on (Dessai and Van der Sluijs 2007) this catalogue has been further developed into specific techniques that help the user to assess and deal with uncertainties in climate change and adaptation decision-making.

These tools, methods and approaches are listed bellow (no prescribed order) and comprise the list that was applied to the reporting of the real-life cases in Chap. 4:

- Scenario analysis ("surprise-free")
- Expert elicitation
- Sensitivity analysis
- Monte Carlo
- Probabilistic multi model ensemble

[2] This tool catalogue can still be downloaded at: http://www.nusap.net/downloads/toolcatalogue.pdf

- Bayesian methods
- Numeral Unit Spread Assessment Pedigree (also known as NUSAP/Pedigree Analysis)
- Fuzzy sets/imprecise probabilities
- Stakeholder involvement
- Quality Assurance/Quality Checklists
- Extended peer review (review by stakeholders)
- Wild cards/surprise scenarios
- For a comprehensive analysis of these methods and their application to adaptation decision-making see Dessai and Van der Sluijs (2007).

Attention should be paid to the fact that both the methods for uncertainty assessment mentioned here and the frameworks for decision-making under uncertainty presented in the next section have different capabilities in the extent to which they can deal with each of the uncertainty typologies described in Sect. 2.3.

In Chaps. 4 and 5 you can find further information on how these methods and frameworks have been applied in practice and how they have contributed to real adaptation decisions.

2.5 Decision-Making Frameworks Under Climate Change Uncertainty

Climate variability is a challenge to the management of risks and uncertainties and may even be amplified by climate change. As such, management depends on the availability of data but it may also be region dependent. Statistical uncertainty can be quantified as a probability density function and can be addressed in policy by a classic risk approach. Some examples are as follows:

- The maximum allowable inundation probability of the urban area in the West of the Netherlands is set to once in 10,000 years. Consequently, the tide with a historical frequency of once in 10,000 years is chosen as the design water-level for determining the level of the dikes and coastal defences.
- The bearing-strength for flat roofs of buildings to be prescribed in the building code can be based on historic data of frequency and amounts of peak snow fall.
- The drainage sewage system in a city can be based on the frequency and intensity of past intense rainfall events to keep the risk of wet feet on an acceptable level.

Future developments of the main drivers of climate change (economic growth and population growth) are inherently uncertain. These can only be explored using projections and scenarios, but the most frequent probability of each scenario is simply unknown. Further, our detailed understanding of the climate system is rather incomplete and all kinds of surprises and unforeseen responses of the climate system and unanticipated impacts may pop up. This is classified as ignorance. The classic risk approach alone is then no longer adequate and needs to be modified

Table 2.1 Different approaches: the spectrum from top-down to bottom-up

Framework	Strategy	Approach
Top-down (predict and quantify changes in stressors)	Act on the best prediction	Based on single scenario
	Robustness-oriented adaptation	Based on range of scenarios
		Exploratory/discursive
Bottom-up (analyse and reduce vulnerabilities of impacted system)	Resilience-oriented adaptation	Preparing for unknown changes

by approaches that can cope with scenario uncertainty and ignorance. Understanding the relative importance of statistics, scenarios and ignorance in a given adaptation situation is crucial for the choice of a suitable policy strategy to address these uncertainties. This can be different for each particular adaptation problem.

2.5.1 Top-Down and Bottom-Up Approaches

The decision frameworks and analysis tools to deal with uncertainty can be roughly grouped into two schools of thought (see Table 2.1):

- Top-down approach
- Bottom-up approach

The difference between top-down and bottom-up approaches is in the direction in which the causal chain is followed in the reasoning. The top-down approach explores the accumulation of uncertainty from top to down, i.e. from emission scenarios, to carbon cycle response, to global climate response, and to regional climate scenarios. The end result is a range of possible local impacts which enable needs to be anticipated and quantified.

On the other hand, the bottom-up resilience based approach starts at the other end of the causal chain: the impacted system, and explores how resilient or robust this system is to changes and variations in climate variables. It determines how adaptation can make the system less prone to uncertain and largely unpredictable variations and trends in the climate. Resilience also means that the impacted system is suitably adapted to ensure that its essential functions can recover more quickly after a shock. It also ensures quick restoration after damage and rapid response times following early warning signals.

Table 2.1 demonstrates how the different approaches detailed below can be classified on the analysis spectrum. Examples of all types of approach are provided in Table 2.2. For reasons of clarity, the wording ‘predict’ is also often used as ‘project’, and the two approaches are used both as providing complementary insights, i.e. not mutually exclusive.

Table 2.2 Top-down and bottom-up climate adaptation examples

	Best prediction	Robustness	Resilience
Flooding	Set flood safety standards based on historical records, or extrapolation of these using a 'best-guess' of the future situation.	Heighten dikes or raise ground level based on national scenarios.	Evacuation and contingency plans.
		Potentially reserve land for further dikes (spatial claims).	Recovery plans.
			Monitoring and warning systems.
			Compartmentalisation.
			Floating (or floatable) buildings.
			Flood-proof materials for infrastructure and 1st floors of buildings.
Extreme precipitation	Set carrying capacity of flat roofs based on historical records, or extrapolation of these using a 'best-guess' of the future situation.	Set sewer dimension standards to cope with increased and intensified rainfall.	Raised pavements.
	Same for sewer dimensions.		Permeable pavements and/or more soft surfaces (e.g. public or private green).
			'Water squares' and similar temporary retention options.
Drought	Design water storage facilities to allow coping with the best estimate for drought occurrence.	Assess the ability of freshwater supply system to cope with range of future circumstances (under current conditions and proposed changes).	Diversify sources for fresh water.
		Change setup and standards for the power supply system to cope with warmer water and lower water tables (for power plant cooling).	Diversify power generation techniques (i.e. include more that do not depend on water cooling).

(continued)

Table 2.2 (continued)

	Best prediction	Robustness	Resilience
Heat waves	Set building standards for isolation, ventilation, and/or cooling options based on expected maximum heat wave in future.	Design cooling systems for buildings to cope with a range of future heat circumstances.	Heat Action Plan with advice and options for staff of senior citizen homes. Increase open water and vegetation in urban areas. Plan orientation of streets/ buildings to allow for 'urban ventilation'.

Source: Based on Dessai and van der Sluijs (2007), Wardekker et al. (2010), Runhaar et al. (2012)

Act on The Best Prediction

In some top-down adaptation frameworks, climate change scenarios are considered the main driver of biophysical and socio-economic impacts, thus being of key importance in devising adaptation strategies (Dessai 2005). If policy-makers select a single scenario as the basis for the design of adaptation policies, we call this strategy "*act on the best prediction*". Note that '*best*' does not necessarily refer to '*most likely*' but can also be interpreted as '*considered to be the most relevant for the decision at hand by the policy-maker*'.

Robustness-Oriented Adaptation

Robustness-oriented adaptation strategies focus on climate-proofing to a range of possible futures. That means that the system keeps performing within acceptable limits or can be restored within an acceptable time frame, given the known climate variability, the range of relevant climate scenarios, and considering possible surprises or wild cards. The main strength of these approaches lies in coping with scenario uncertainty.

A top-down way of robustness-oriented adaptation is to use climate scenarios for dimensioning adaptation measures. Internationally, traditional scenario analyses such as those performed by the IPCC (2005) have become an important tool in climate change-related decision-making. At the national and urban scale, some countries and cities have also developed regional climate scenarios. Traditional scenario methods allow for a relatively technocratic approach, using in-house experts or consultants.

Robust decision-making can also include participative approaches with a broader set of stakeholders. Overall, the approach can be used to scope relatively large-scale options and structural measures, as well as for the critical evaluation of proposed options packages.

Resilience-Oriented Adaptation

The other school of thought is resilience-oriented. Resilience is defined as the capacity of a system to tolerate disturbance without collapsing into a qualitatively different, usually undesired state. Some uncertainties associated with climate change are accepted as being irreducible; therefore the emphasis is on learning from past events. This thinking comes from the fields of societal and policy learning, adaptive management for natural resources, and complex adaptive systems research. If uncertainties regarding climate impacts are so big that science is unable to provide any reliable estimates, there might still be enough knowledge to strengthen the general resilience of the impacted system. A resilience approach can make a system less prone to disturbances, and enables quick and flexible responses. Including resilience in climate adaptation will make the adapted system better able to deal with surprises than when using traditional predictive approaches alone.

2.6 Using Uncertainty Assessment in Decision-Making Practice on Climate Adaptation

National and local governments are increasingly seeking building blocks for a resilient climate risk reduction policy. Such as policy needs to be based on more insight into the uncertainty of and vulnerability to climate change in the short and longer term. Adaptation measures are also being increasingly examined in relation to coupling and synergy with various policy areas, such as those of nature, agriculture, urban development, transport and the quality of life. The reduction of greenhouse gas emissions is a component of measures to be considered in relation to climate mitigation policy. For the ultimate policy choices, it is important to acquire a clear picture of the advantages and disadvantages of various packages of adaptation measures, and possible positive or negative feedbacks between various policy fields when uncertainties are taken into account.

Climate change is a relatively slow process. There are long-term impacts on societal restructuring and capital investments are relatively irreversible. Since (some) choices have to be made now, to ensure future climate resilience, flexible policy decisions are required. To develop these, the following factors are necessary:

- Targeted framework,
- Adequate impact and adaptation models,
- Relevant decision-making criteria and adaptation principles, including an uncertainty assessment, and
- Support from all relevant stakeholders.

Decision-making, policy and practice make increasingly use of a structured risk management framework. The usually includes a step-by-step process to help to assess what adaptation measures are most appropriate given the risk management goals and targets. A well-known risk management framework in climate adaptation is the one developed by UKCIP (http://www.ukcip.org.uk/risk). In the steps of identification and appraisal of adaptation options and adaptation strategies, uncertainty assessment, and how to deal with it in adaptation policy, is a crucial process.

Principles for weighing and appraising climate adaptation options and adaptation policies can be condensed into the following five elements:

- ***Risk reduction*** – impact and costs of adaptation options to reduce climate risks, economic and environmental damage, and societal encroachment.
- ***Dealing with uncertainty*** – assessment of uncertainty typology; addressing uncertainty in decision-making frameworks, weighing and appraisal criteria, prioritisation principles, and dealing with uncertainty strategies.
- ***Governance feasibility*** – institutional ability; roles and responsibilities of policy and decision-makers and stakeholders.
- ***Realisation and mainstreaming*** – stakeholder support, equity principle, urgency aspects, implementation time, relevant spatial scale, financial (business) model, 'no-regret' or 'low-regret' adaptation options, and co-benefits of mainstreaming adaptation with other policies.
- ***Monitoring, evaluation, and communication*** – framework, indicator set, and action plan to monitor and evaluate the progress and efficacy of climate adaptation policy.

In the preceding paragraphs we have outlined ways to deal with various types of uncertainties and decision frameworks. In practice, climate adaptation assessments do not only have to deal with uncertainties, but also with time and budget constraints. It might often not be possible to employ all possible methods to deal with all the uncertainties inherent in the assessment. Therefore, it is necessary to prioritise uncertainties and the work needed to assess or reduce them. This can be done in the following three steps:

- Identify and characterise sources of uncertainty;
- Assess (weigh, appraise, and prioritise) sources of uncertainties;
- Select and apply methods for dealing with uncertainties.

In all these steps, the uncertainty typology (see Sect. 2.3) can be used to support the process. Subsequent communication of the results to policy-makers will be discussed in the following paragraphs.

Firstly, the different sources of uncertainty need to be identified. It is likely that a long list of uncertainty sources will be generated and this can be done using two different approaches:

- By analysing each step of the climate assessment at hand and subsequently characterising each source according to the typology, and
- By considering each possible type from the uncertainty typology and discussing where in the assessment this type of uncertainty may occur.

Reasoning from both angles may help to minimise the chance that a source is overlooked. The resulting list of uncertainties can be further characterised using the uncertainty assessment (Sect. 2.3).

Secondly, the relative importance of each uncertainty element can be weighted based on its potential impact on the outcome of the climate assessment in question. Where some form of quantification is possible, the relative importance can be assessed by means of sensitivity analysis. However, for many sources of uncertainty, such quantification is not feasible. In such a case, the relative importance can and should be assessed using expert judgement to consider the importance as being either of crucial, average, medium or low importance. Results from individual experts can be combined to arrive at a group ranking of the items on the list of uncertainties. Arguments used by the experts to defend their ranking need to be documented and special attention should be given to reasons for any substantial disagreement on the importance of a particular uncertainty source.

Thirdly, after the weighing, appraising, and prioritisation, suitable tools can be selected for further analysis of the key uncertainties. Each uncertainty type may require a different method to address it, and to gauge its impact on decision-making. The uncertainty tool catalogue described in Sect. 2.3.4 provides guidance for selecting appropriate methods that match the characterisation of the uncertainty in the typology.

It may, however, not be possible to correctly identify, characterise and prioritise all sources of uncertainty at the beginning of an assessment. The typology may thus need to be reassessed throughout the project. New sources of uncertainty may be added or their weights may be adjusted. The uncertainty typology should therefore be used interactively throughout the study. As such, it also provides a framework for keeping track of all sources of uncertainty, so that those identified early in the project – especially if not immediately quantifiable – are not forgotten at the end of the study when results are reported.

2.7 Cases, Types of Uncertainty, and Methods as Used in Chap. 4

The aforementioned uncertainty assessment methods can be recognised in the various case studies described in Chap. 4. The overview displayed in Table 2.3 gives specific information on every case study.

2.8 Communicating Uncertainty Assessment to Policy-Makers and Decision-Makers

Most policy-makers and decision-makers will feel more comfortable when making decisions based on single, undisputed numbers with small uncertainty ranges, than on ambiguous or controversial estimates and scenario analyses. Unfortunately, however, complex processes cannot often be described this way. There again, giving

Table 2.3 Chapter 4 case study overview

Case studies	Level of Uncertainty	Methods used
Water Supply Management in Portugal (4.2.1)	Scenario	Scenario analysis ("surprise-free") Expert elicitation Sensitivity analysis Stakeholder involvement Extended peer review (review by stakeholders)
UK Climate Change Risk Assessment (4.2.2)	Statistical Scenario	Scenario analysis ("surprise-free") Expert elicitation Sensitivity analysis Bayesian methods NUSAP/Pedigree analysis Stakeholder involvement Quality assurance/Quality checklists Extended peer review (review by stakeholders)
Water Resources Management in England and Wales (4.2.3)	Statistical	Monte Carlo Probabilistic multi model ensemble
Water Supply in Hungary (4.2.4)	Scenario	Expert elicitation Sensitivity analysis Probabilistic multi model ensemble Fuzzy set/imprecise probabilities Stakeholder involvement
Climate Change and Health in The Netherlands (4.2.5)	Scenario Recognised ignorance	Expert elicitation Stakeholder involvement
Flood Risk in Ireland (4.2.6)	Scenario Recognised ignorance	Sensitivity analysis Wild cards/ Surprise scenarios
Coastal Flooding and Erosion in South West France (4.2.7)	Scenario Recognised ignorance	Expert elicitation Stakeholder involvement
Québec Hydro-Electric Power (4.2.8)	Scenario	Scenario analysis ("surprise-free") Expert elicitation Sensitivity analysis Probabilistic multi model ensemble Stakeholder involvement
Austrian Federal Railways (4.2.9)	Scenario	Expert elicitation Sensitivity analysis Bayesian methods Stakeholder involvement
Dresden Public Transport (4.2.10)	Scenario Recognised ignorance	Scenario analysis ("surprise-free") Expert elicitation Sensitivity analysis Fuzzy sets/imprecise probabilities Stakeholder involvement Wild cards/ Surprise scenarios Fuzzy cognitive mapping

(continued)

Table 2.3 (continued)

Case studies	Level of Uncertainty	Methods used
Hutt River Flood Management (4.2.11)	Statistical Scenario	Scenario analysis ("surprise-free") Sensitivity analysis Probabilistic multi model ensemble Stakeholder involvement
Communication of Large Numbers of Climate Scenarios in Dutch Climate Adaptation Workshops (4.2.12)	Scenario	Scenario analysis ("surprise-free") Expert elicitation Sensitivity analysis Stakeholder involvement

policy-makers a lengthy report listing all the possible uncertainties will not necessarily lead to informed policy-making either.

Scientists can help policy-makers (and their respective target groups like shareholders and the general public) by assessing which uncertainties are most relevant for the policy decisions concerned. They can identify policy options that are robust given these uncertainties. If no single best policy option for all scenarios can be determined, all reasonable options can be discussed in a democratic, participatory process including scientists, stakeholders, policy makers and politicians (Pielke et al. 2007). As the communication needs of all these parties can vary greatly, a single mode of risk communication is rarely sufficient.

Uncertainties can be communicated linguistically, numerically, or graphically. Confidence intervals can be provided reflecting uncertainty in parameters and input data. For uncertainties that cannot be expressed in statistical intervals, other characterisations of likelihood can be used. Risbey et al. (2005) have proposed expressions for different levels of precision, ranging from full well defended probability density functions, to percentile bounds, first order estimates, expected signs or trends, ambiguous signs or trends and, finally, effective ignorance. Additionally, if policy recommendations are made, the strength of these recommendations and the quality of the underlying evidence can be expressed using qualitative grading (Atkins et al. 2004; Guyatt et al. 2008).

In order not to overwhelm the user of the assessment results with uncertainties, the concept of progressive disclosure of information can be employed (Wardekker et al. 2008; Kloprogge et al. 2007). This involves tailoring the information about uncertainty to the target audience. In a press release or a project summary, for example, the uncertainties that are most relevant to the final policy decisions need to be described, without any technical details. This way, a policy-maker using the results of a climate assessment will not be directly confronted with a typology of all uncertainties, but will be provided with the information needed to properly interpret the results. The main assessment or background report may subsequently contain more detailed information, with emphasis on the nature, extent and sources of uncertainties. Ideally, it presents all methods, assumptions, parameters and input data, thereby providing maximum transparency of the assessment approach.

2.9 Conclusions

In this chapter we have examined various aspects of dealing with uncertainty in support of decision-making on climate adaptation. To be effective, adaptation should ideally be part of any urban and rural economic development policy and related sectoral plans and budgets. Vulnerability to climate change will be greatly affected by the development and implementation of behavioural, technical, and spatial adaptation strategies and policies. Uncertainty assessment and dealing with uncertainty are integral parts of establishing and implementing targeted climate adaptation policies.

The uncertainty assessment and dealing with uncertainty in adaptation policy can be dealt with in the following ways:

- **Top-down**, prediction-oriented approaches which are strong in statistical uncertainty and can reasonably cope with scenario uncertainty, but cannot handle ignorance.
- Resilient and robust types of **bottom-up** approaches which are strong in coping with recognised ignorance and surprises.

Without knowing too much of the magnitude and nature of climate change impacts, we can still formulate reasonable policies to make the system less prone to possible changes. An essential first step in the selection of an appropriate decision-making framework and methods for uncertainty analysis needs to be based on the policy-relevance of each of the three levels of uncertainty, along with a judgment of their relative importance.

Different strategies and approaches to uncertainty require different scientific methods for assessment. The top-down approaches require probabilistic estimates and (surprise-free) scenarios, such as Bayesian methods and Monte Carlo analysis. The bottom-up approaches use qualitative uncertainty methods such as the NUSAP approach. They also use participatory knowledge production and knowledge assessment, wild cards and surprise scenarios.

Different approaches are available for dealing with uncertainty in adaptation policy. For example, case 4.2.5 shows how resilience can be used for climate adaptation in urban areas in the face of all types of uncertainty, but the effectiveness and efficiency is very difficult to assess in quantitative terms. Predict and control may be appropriate in some management situations while adaptive/resilience-oriented approaches are useful in others. For example, resilience is highly suitable for tailoring bottom-up type of adaptation to the local situation, while the more rigid prediction-oriented approaches is sometimes used by top-down oriented approaches by national and regional governments.

Other factors also influence the usefulness of various strategies: the relevance of the expected impacts; the expected encroachment on society; and, extensiveness of required interventions. For example, we need to ask ourselves whether an approach can be easily implemented in an existing situation, or whether we would need rigorous reforms, redevelopments, or changes in the way we ‘do things’, and what the costs and co-benefits of actual options would be.

This is demonstrated in case 4.2.5 where precautionary measures deal well with ignorance but can involve high costs and potential side-effects; such approaches are advised for impacts that are both highly uncertain and highly relevant.

For possible climate-related impacts characterised by ignorance, the results of a climate change and health study could be extrapolated towards a more general view (Wardekker et al. 2012; this view is also visualised in a scheme described in the Dutch case study in Sect. 4.2.5):

- Adaptation policies that focus on enhancing the system's and society's capability of dealing with possible future changes, uncertainties and surprises (e.g. through resilience, flexibility, and adaptive capacity) seem most appropriate.
- For climate-related effects for which rough risk estimates are available, 'robust measures are recommended.
- For effects with limited societal or policy relevance, 'no-regret' measures are recommended.
- For highly policy-relevant climate effects, precautionary measures can be considered. However, for such options, it would be advisable to assess the risks of over-investment to avoid excessive costs and to ensure their flexibility.

We advise assessing the availability of 'no-regret' adaptation options as well as the adaptation options that have co-benefits with other policy issues. For quantifiable effects it seems useful to combine system-enhancement with approaches such as 'robust decision-making'. Knowledge gaps on the effectiveness of adaptation options will likely limit adaptation to a qualitative/ semi-quantitative exploration. An exploration of uncertainty typology could contribute to policy/political discussions on the preferred ambition level of adaptation strategies, also considering the range of potential impacts.

There is a growing feeling that a sort of '*dynamic and incremental adaptive strategy*', taking various sorts and levels of uncertainties into account, is a very promising targeted policy approach, especially for new and ambiguous risks. Analysing and characterising uncertainty by means of a specific typology can be a useful approach for the selection and prioritisation of preferred adaptation policies to reduce future climate related risks. It can also help policy-makers and practitioners to make more educated decisions.

This book will help scientists, decision-makers and policy-makers deal with uncertainty and will show how others, in their specific adaptation cases, have tackled this issue.

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