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published in
Regional Environmental Change
2014

DOI (link to publisher)
10.1007/s10113-013-0519-2

document version
Publisher's PDF, also known as Version of record

Reg Environ Change
DOI 10.1007/s10113-013-0519-2

ORIGINAL ARTICLE

Framing climate uncertainty: socio-economic and climate scenarios in vulnerability and adaptation assessments

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Received: 25 July 2012 / Accepted: 25 July 2013

Abstract Scenarios have become a powerful tool in integrated assessment and policy analysis for climate change. Socio-economic and climate scenarios are often combined to assess climate change impacts and vulnerabilities across different sectors and to inform risk management strategies. Such combinations of scenarios can also play an important role in enabling the interaction between experts and other stakeholders, framing issues and providing a means for making explicit and dealing with uncertainties. Drawing on experience with the application of scenarios to climate change assessments in recent Dutch research, the paper argues that scenario approaches need to be matched to the frames of stakeholders who are situated in specific decision contexts. Differentiated approaches (top-down, bottom-up and interactive) are needed to address the different frames and decision-making contexts of stakeholders. A framework is proposed to map scenarios and decision contexts onto two dimensions: the spatial scale of the context and the starting point of approach used in scenario development (top-down, bottom-up or incident-driven). Future climate and socio-economic scenario development will be shaped by the need to become better aligned with multiple interacting uncertainties salient to stakeholders.

Keywords Climate change · Climate scenarios · Socio-economic scenarios · Framing · Uncertainty · Vulnerability · Adaptation

Introduction

Projections of future climates and societies play a fundamental role in public and policy debates about climate change. Major efforts have been made, in the context of the Intergovernmental Panel on Climate Change (IPCC), by national agencies and through scientific research to develop realisations of future climates and to link these to assessments of future risks to social systems and ecosystems (Nakicenovic et al. 2000; Hulme et al. 2002; van den Hurk et al. 2006; Moss et al. 2010; Heinrichs et al. 2010; IPCC 2012a). Scenario approaches have stood at the heart of projections of both climate and socio-economic futures because they are a powerful way of representing uncertainties in complex, dynamic systems. An important analytical challenge in combining climate scenarios and socio-economic scenarios is that they each deal with different

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forms of uncertainty (Berkhout et al. 2002; van Vuuren et al. 2011). While climate scenarios are concerned primarily with uncertainties in physical and biogeochemical systems, socio-economic scenarios are concerned with uncertainties in economic, social, political and cultural systems in which reflexivity and innovation are fundamental features.

Early assessments of climatic changes and the associated risks for ecosystems and economic activities were regional and global in scope (Rosenzweig and Parry 1994; Arnell 1998). A 'top-down' approach was used in the development of climate and socio-economic scenarios to represent and analyse climate and social change and how these together influenced the vulnerability of social and ecological systems. This matched the framing of climate change as a global environmental change problem. Over time, the social and spatial specificity of the changes in climate and the risks[1] they pose for ecological and societal systems have become more evident. And this has produced a growing interest in projections at regional and national scales (Gleick 1987; Kwadijk 1993), with growing efforts to 'tailor' outputs from scenarios to specific user needs (Van den Hurk et al. 2013a). Increasingly, climate change, vulnerability and resilience have been viewed from the 'bottom-up', taking this regional or sector-specific vulnerability and resilience as a starting point for scenario development.

The application of climate and socio-economic scenarios to the specific decision contexts of practitioner and decision-makers has generated new questions. A key issue is the uncertainty in weather and climate projections at shorter time scales and more specific spatial scales (e.g. Haasnoot and Middelkoop 2012; Maslin and Austin 2012). Even for quite fundamental parameters, such as annual mean precipitation, climate models may give a wide range of results for certain regions (Deque et al. 2007). The mismatch between the current capacity to make reliable predictions of weather and climate, and users' needs for information is illustrated in Fig. 1. Moreover, finding a 'fit' between the life-world of decision-makers and the outputs of scenario-based assessments remains a major challenge. There appears often to be a mismatch between model and scenario outputs, and the needs of decision-makers for information about uncertainties. Finally, weather and climate variability may interact in complex ways with social and institutional factors to generate hazards or opportunities for specific social actors or under specific conditions. Important hazards and risks are frequently the outcome of event sequences that may be hard to analyse or generalise.

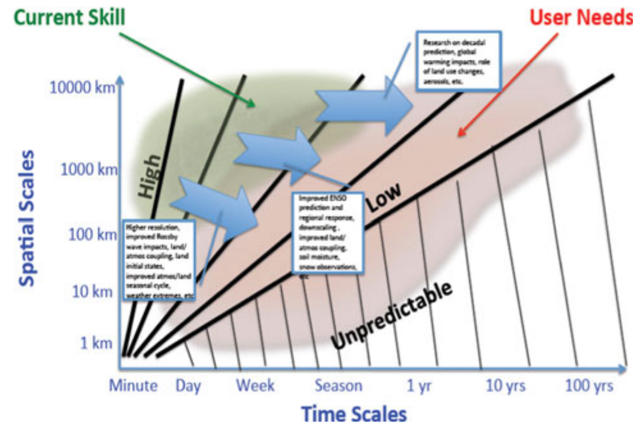

Fig. 1 Predictability of weather and climate models across spatial and temporal scales: a mismatch between model skill and user needs. 'Skill' relates to the statistical quality of predictions made by weather and climate models (*Source* ICPO 2010)

Given these difficulties, there has been a growing demand for more bottom-up, incident-driven or interactive scenario approaches, which start from the decision context of the stakeholder, rather than with aggregated representations of climatic or social and economic conditions. At the same time, the greater emphasis on social, spatial and temporal specificity in scenario use has produced a countervailing demand for more standardised approaches to enable comparison and learning across different cases. Balancing these conflicting priorities has generated new research needs and methods.

In this paper, we argue that a range of scenario approaches are available to address different decision-making contexts in government, business, civil society and by citizens. While there are decision contexts for which conventional top-down approaches are appropriate, there are other contexts that are more local, where weather variability is a major source of risk and where multiple factors interact in generating vulnerabilities. There are still other intermediate cases, typically at the national or regional scale, for which a combination of top-down and bottom-up approaches is appropriate. The needs of decision-makers in these cases are not well served by conventional approaches. We argue that 'interactive' scenario methods are needed for these mid-range assessments.

In this paper, we develop a typology of scenario approaches and illustrate these for a number of examples covering different context frames, perceptions of uncertainty, scales and decision contexts. Scenarios can be viewed as an instrument for framing uncertainties salient to decision-makers, allowing them to integrate knowledge about climate variability and change into their own decision context. Unravelling the flexibility and context dependency of frames is difficult, because they can be

[1] See http://ace.geocat.net/glossary#linkRisk for a definition of vulnerability and risks, compiled by the European Climate Adaptation Platform.

expressed by a variety of representations (e.g. how a problem is stated, who is expected to make a statement about it, what questions appear relevant and what range of answers might be appropriate). For our purpose, we have chosen to look across a range of contexts with the aim of illustrating contrasting patterns of reasoning, such as top-down as compared with bottom-up approaches. We stress the practical use of scenarios and draw on examples including the new IPCC Representative Concentration Pathways (RCP) and Shared Socioeconomic Pathways (SSP), the Dutch Climate Scenarios, Dutch Delta Scenarios, a study on wind climatology for the Dutch offshore wind industry, a study of compound events related to flooding in North Netherlands, the Revised Hydrological Year and Adaptation Tipping Points associated with the Thames 2100 study.

The paper is organised as follows. In the next section, we outline how actor frames are related to decision-making contexts. We then describe 'top-down', 'bottom-up' and 'interactive' (generally a combination of bottom-up and top-down) approaches to developing scenarios, which frame uncertainties about future climate, and the resilience and vulnerability of biophysical and social systems. We then argue that different scenario approaches are appropriate to different decision-making contexts and conclude with a framework for mapping scenario approaches to decision contexts. The examples used for illustration will be revisited in the final discussion section, specifically comparing the scenario approaches and the match to the specific decision contexts.

Framing and decision contexts

Developing scenarios that generate information useful to different social actors requires a clear understanding of their frames and decision-making contexts. Frames are mental knowledge structures that capture the typical features of a situation or event sequence, defining a set of relevant concepts and problems, and thereby shaping knowledge and experience (Barsalou 1992; Bednarek 2005). The way in which a problem is framed (i.e. the problem frame) accentuates particular highlights, opportunities, vulnerabilities, uncertainties and attention points that can either help or hinder sense-making about a problem and the search for a solution. In any social situation, frames are not just personal mindsets, but also cultural structures that enable individuals to take shared or opposing political and philosophical positions (Schön and Rein 1994). As a result, the use of scenarios in decision-making on climate change should take into account that a problem framing is often constrained by interests and experiences of actors in the decision-making context,[2] such as their willingness to take risks, experience in dealing with uncertainty and other social and cultural factors.

Scenarios can be viewed as frames enabling projections of future climate and its impacts to be shared and debated (de Boer et al. 2010). Without explicit frames, structured exchange of evidence and argument is difficult, and it will be hard to motivate action. Scenarios work to frame the relationship between science and decision-making by adapting formalised knowledge to the decision context and by assisting the search for responses that are practicable for the decision-makers. However, the gap between science and committed action by decision-makers is often felt to be large. It is a common fate of decision tools that first-best options are not always chosen. We can learn from 'naturalistic decision-making' (Lipshitz et al. 2001) that the quality of a decision depends not only on its internal logic or consistency, but also on the commitments it generates among decision-makers to act in line with the outcomes. Our observations indicate that committed action is easier to generate when the starting point is not a top-down frame, but a more familiar event-based frame, evoked, for instance, by extreme weather that clearly indicates how decision-makers' options are affected by weather variability.

In their role as decision support tools, scenarios have to compete with other ways in which decision-makers may reason about the future. According to Rumelhart (1989), there are three common processes for reasoning about novel situations:

Reasoning by similarity: a problem is solved by seeing the current situation as similar to a previous one in which the solution is known. In this category fall intuition, reasoning by example or experience, generalization and analogical reasoning.

Reasoning by simulation: a problem is solved by imagining the consequence of an action and making explicit the knowledge that is implicit in our ability to imagine an event. This category includes story-building to mentally simulate the events leading up to a certain ending.

Formal reasoning: a formal symbolic system, such as logic or mathematics, is employed in the solution of a problem. Examples are formal mathematical models of biophysical or social systems, including climate scenarios.

[2] By decision context, we mean the institutional setting of a decision-making process, including the actors who are involved in that process. A commission of experts developing a new national strategy for flood risk management over the next 50 years, such as the Dutch Delta Commission (2007–2008), represents a different decision context than a farmer planning what crops to grow in the coming season.

Reasoning by similarity and by simulation are important ways in which skilled decision-makers can build on their experience to make decisions. Formal approaches are extensions of these two ways of reasoning. For instance, influence inference diagrams and computer simulation models build upon mental simulation of processes in the real world by using mathematics and formal analysis. However, depending on the decision context, there may be a tension between naturalistic decision-making (using intuition or simulation) and formalised decision-making (using formal reasoning). According to Lipshitz et al. (2001), a formalised approach is more likely to be used with problems that are highly combinatorial, in situations where justifications are required, and in cases where the views of different stakeholders have to be taken into account. This assumes that formalised approaches are widely held to be valid. However, while the integration of formal climate models with economic models has come to be seen as valid in assessments of the costs and benefits of efforts to reduce greenhouse gas emissions (Nordhaus and Yang 1993; Tol 2009; Nordhaus 2010), such validity has not yet been demonstrated for assessments based on the integration of climate models with models that represent impacts, adaptation and vulnerability (IAV) to climate change (Patt et al. 2010). This difference in relative status may also partly explain their reduced salience for decision-makers.

Conventional top-down scenarios are based on formal reasoning and have been oriented to complex, multi-stakeholder, broad-scale and long-term decision contexts, such as the IPCC and international climate policy. Similar approaches have been used in IAV assessments at both global and local levels. But many decision contexts related to climate risk, vulnerability and adaptation are related to local and short-term problems involving a specific community of actors. There has therefore been a trend towards scenario approaches which include more naturalistic elements. Such bottom-up scenarios can also create and maintain commitment by providing a means of reasoning by similarity or by simulation. This shift may involve a change of frames, replacing a probabilistic view by an intuitive deterministic view; or an outside view by an inside view. That is, instead of looking at a system, such as a dike ring, from the outside, as one out of many dike rings, one may look at the system from within, as an inhabitant, simulating what might happen in a particular location on the basis of local knowledge and values. Such an insider's view of the system would start from the life-world of the inhabitant.[3]

[3] By life-world, we mean the shared common understandings, including values, held by and holding together any social group (Schütz and Luckmann 1973; Habermas 1981). Life-worlds are more generic than the frames they support.

In many decision-making contexts, a combination of the formal top-down and naturalistic bottom-up approaches may be drawn on. Relying solely on formal scenarios introduces the risk of overlooking relevant parts of the ranges explored and may lead to over-generalisation. A focus on naturalistic approaches allows inclusion of a wide range of locally relevant aspects into the decision process, but introduces the risk of missing the bigger picture and a selective reading of relevant information. Appropriate combinations of these two approaches provide the balance for decision-makers, provided that they understand that inside and outside views draw on different sources of knowledge and are directed at different contexts of decision.

Top-down, interactive and bottom-up scenario approaches

Complex systems such as the climate or a society are not predictable in a conventional sense. This problem becomes even more acute when climate and society are seen as interacting systems. Where the decision context relates to social, spatial and temporal scales not usefully served by deterministic or probabilistic predictability, scenario approaches are typically used. Conventionally, climate scenarios often assume a fundamental driver of future conditions to obtain a certain value (a 'what if?' condition), such as global fossil fuel consumption and the climate system response to this by the end of the twenty-first century. For the well-known IPCC scenarios (IPCC 2007), an extended hierarchy of assumptions and modelling tools is used to depict future climatic conditions in response to a chain of interacting processes: assuming given socio-economic and technological developments, global greenhouse gas emissions are estimated to have a value labelled as *W*, to which the climate system responds within a range *X*, which is downscaled to the regional level to estimate a local climate response *Y*, which translates into impacts on the regional socio-economic or natural system within another range *Z*. We view this approach as a top-down approach to scenario projection. The breadth of the range of responses (often labelled as *uncertainties*) tends to increase down the scenario chain (Schneider and Mastrandrea 2005).

At the global scale, climate variability affected by spatially varying processes and by interactions with surrounding regions is averaged out, but at the regional scale, this variability is evident. Regional climate change scenarios aim to translate global changes to the national or regional scale (Such as the Dutch Climate Change scenarios; KNMI 2006; Van den Hurk et al. 2007, 2013b). They include an explicit dependence on external steering variables that span a range of uncertainty originating from regional boundary conditions. This increased complexity means that at the regional level, different climate models produce even stronger differences than at the global scale. Such climate uncertainties are compounded in assessments of impacts with the greater variety of social, economic and governance factors that need to be taken into account at the regional or national level in order to generate assessments that engage with the decision contexts and frames of practitioners and stakeholders. It is beyond the scope (and ability) of formal analysis to address such complexity of phenomena and their interactions.

Climate impacts, vulnerability and adaptation choices can also be framed in the opposite way. A reverse chain of analysis uses the vulnerabilities or opportunities of relevant sectors as a starting point (Pielke et al. 2012; Wilby and Dessai 2010). Examples of this approach include the Thames Estuary 2100 study (UK Environment Agency 2009), which assessed alternative pathways for adaptation to uncertain sea-level rise for the Thames Barrier and the 'adaptation tipping point' analysis which has been applied to Dutch water management (Kwadijk et al. 2010). This bottom-up approach assumes that multiple drivers of risk and change are salient to the decision context and frames of practitioners and policy-makers. Climate-related risks are introduced only where these are relevant to a decision context. Such approaches start with what is known about the resilience or vulnerability of a given system, and then seek to assess the capacity of the system to cope with climate stresses in the current state, or under alternative adaptation scenarios.

One advantage of bottom-up approaches is that they specify the uncertainties and ensure a focus on that fraction of the uncertainty that is relevant for the decision context of an identifiable social actor. Such assessments do not attempt to cover the full range of uncertainties, but concentrate on the occurrence of conditions that have a major impact for a system, region or activity covered by the assessment. By building scenarios out of the life-worlds of stakeholders that are well fitted to decision contexts, the potential for generating commitment to action is also greater.

Another distinction between 'top-down' and 'bottom-up' approaches is the level of conceptualisation. Top-down approaches seek to map changes of major drivers of the climate and of socio-economic systems, and technical consensus on the choice of these factors provides a generalised framework for scenarios. From these general conditions, more specific analyses are then derived. A bottom-up approach, by contrast, starts with a potentially impacted system, region, sector or actor for which a range of specific factors may be significant drivers of risk or resilience. Such an approach could also include the exploration of observed or synthetic event sequences generating extreme or catastrophic risks for the system in question. These could include combinations of climatic, and technological and organisational factors. An inventory of vulnerabilities (or opportunities) and event sequences represents a potentially large portfolio of individual cases, for which a general framework is often impracticable. This complexity of bottom-up, resilience-based assessments is also a weakness, since such assessments can be research-intensive, time-consuming and costly. Their results are also more difficult to compare with each other. It has also been argued that vulnerability assessments may promise more than they can deliver (Patt et al. 2010).

While the distinctions between top-down and bottom-up approaches are important, actors' decision contexts do not all fall neatly into such a classification. Across the different scales and sectors in which climate change information may be salient to choices and decisions, mid-range cases exist in which a combination of top-down and bottom-up approaches will be appropriate. These will include national- or regional-level decisions with a decadal time span. Indeed, the most significant public policy interventions in adaptation, related, for instance, to infrastructural investments related to cities, energy, transport, water and nature conservation, will be of this type. For these contexts, we identify a third 'interactive' scenario approach as being appropriate.

Top-down scenario approaches

Global scenarios

For more than two decades, a suite of IPCC emissions and associated climate scenarios has been applied in research and climate assessments. The first emissions scenarios in 1990 (Special Report on Emissions Scenarios, SRES) were top-down, non-policy scenarios (IPCC 1990). These scenarios were further elaborated with the introduction of future socio-economic storylines, leading to a new set of generalised greenhouse gas emission scenarios (Girod et al. 2009; Moss et al. 2010). No consideration was taken of adaptation and mitigation policies in these socio-economic scenarios because they were intended as 'business-as-usual' futures against which the costs and benefits of mitigation and adaptation strategies were to be measured. Given that mitigation and adaptation is already taking place, such scenarios came to be seen as entirely synthetic and not relevant to many decision contexts.

To include the interactions between socio-economic change and climate change as they unfold over time, a new approach was proposed which integrated climate and socio-economic uncertainty while also framing different mitigation and adaptation response trajectories into the future. Four illustrative radiative-forcing trajectories, so-called Representative Concentration Pathways (RCPs), were defined (corresponding to 490, 650, 850 and >1,370 ppm CO_2 equivalents in 2100; Moss et al. 2010). The RCPs have been used as inputs for climate models to provide long-term, global climate change projections. In addition, a mixture of future impacts, vulnerabilities, adaptation and mitigation challenges was developed, with qualitative narratives and quantitative descriptions of socio-economic and ecosystem reference conditions, called 'Shared Socioeconomic Pathways' (SSPs) (Kriegler et al. 2010). The scope of these RCPs and SSPs is global.

Five SSPs have been developed, representing a range of adaptation and mitigation responses determined by different prevailing social, political and economic futures (Fig. 2). In other words, socio-economic futures are framed in terms of their consequences for the capacity to mitigate emissions and the capacity to adapt to the impacts of climate change, in each case ranging from high to low. This implies that mitigative and adaptive capacities are to a large extent independent of each other and that these can be stated in a generalised way. It also implies a wide set of possible outcomes at the global level. The combination of four RCPs and five SSPs yields a two-dimensional matrix (top right matrix in Fig. 2). This matrix, combining climate forcings and socioeconomic pathways, can be used to explore how policies can reduce impacts, or to estimate costs of action or inaction. The final phase in the new scenario development is the extension of the RCP-SSP matrix with climate policy through the development of Shared Climate Policy Assumptions (SPAs, Kriegler et al. 2010). SPAs characterise climate policies, including carbon taxes, energy taxes, emissions trading schemes, R&D subsidies, norms and regulations.

The new RCP/SSP/SPA scenarios (IPCC scenarios 2.0) address the problem of framing climate uncertainty differently to the previous SRES/IPCC climate scenarios (IPCC scenarios 1.0). The IPCC 1.0 scenarios sought to imagine future worlds absent any social and political responses to climate change with a full set of uncertainties for a limited set of climate and socio-economic factors propagated through different global and regional models. The IPCC 2.0 scenarios make a simplifying assumption about the range of forcings that are to be considered (the four standard RCPs) while framing socio-economic futures only in terms of whether they generate an emissions reductions response or an adaptive response. A narrower set of forcings are therefore considered, while background socio-economic worlds are represented in very abstract terms as generating mitigative or adaptive capacities. A challenge in the use of the 2.0 scenarios may be their conceptual complexity.

Downscaling and regionalising global scenarios

Impacts are experienced by social actors, many of whom have decision contexts at local scales. Downscaling

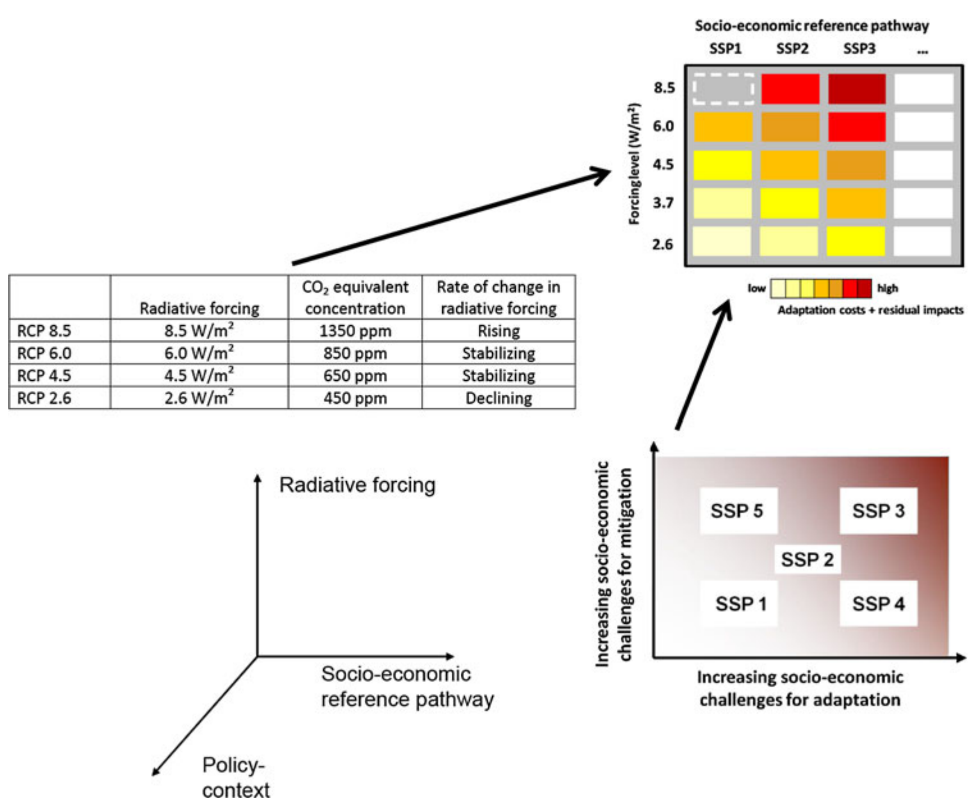

Fig. 2 The total scenario domain, including RCPs, SSPs and SPAs (policy context) (compilation of table 1.1 and Figs. 1.1 and 2.2 in Arnell et al. 2011)

information from global climate models (Wilby and Wigley 1997) or regionalisation (Christensen et al. 2007) was an early response to the need for more fine-grained information useful to practitioners. Downscaling can be done using a variety of methods. One methodological distinction separates statistical from dynamical downscaling. Statistical downscaling uses observed relations between local phenomena (e.g. extreme precipitation) and well-resolved large-scale quantities (e.g. atmospheric circulation) to interpret global climate model output to the local scale. Dynamical downscaling uses regional climate model output at higher resolution, fed by the driving global climate model. Often a mix between the two methods is applied where observations are used to correct biases in global or regional CMs. Different methods exist to construct future climate data sets. The 'delta method' combines an observed reference data set with a climate change signal from climate model projections, whereas the 'direct method' uses climate model output and corrects this for the bias in the present-day and future climate conditions with the help of observations (Leander et al. 2008; Van Pelt et al. 2012).

Along the chain from global climate to regional downscaling, uncertainties are propagated. The downscaling relies on adding new information at the local scale (physiographic data, local observations, knowledge on local drivers) that will cause an anomaly relative to the results of the global climate model. A consensus is emerging that scenario information deduced from a limited set of model projections under-samples the possible resolvable range of changes, and the use of wider ensembles should be promoted. The selection and weighting of these ensemble members remains an active field of research (Van den Hurk et al. 2013b).

The Dutch Climate Change scenarios issued by KNMI in 2006 (KNMI'06) project global climate change information to the regional scale of the Netherlands and surrounding regions using a combination of downscaling techniques: pattern scaling, dynamical modelling, statistical downscaling and user consultation. The involvement of stakeholders was necessary to define the set of relevant climate variables that have a potentially large impact on societal sectors, and this focus on a limited set of climate variables can also be interpreted as a downscaling step. Apart from the general reference scenarios, a number of specific, tailor-made scenarios were constructed, of which a few examples are discussed in more detail below.

Interactive scenario approaches

An intermediate form of climate assessment dealing with strategic, national-scale issues such as flood risk management, calls for a combination of downscaling of (top-down) global climate scenarios and (bottom-up) up-scaling of national or regional socio-economic scenarios. The Dutch Delta Scenarios, designed to support the Dutch national climate adaptation policy, are an illustration of an interaction between top-down and bottom-up scenarios (Bruggeman et al. 2011). The Delta Scenarios combine climate scenarios for the Netherlands (KNMI'06) with socio-economic scenarios developed by national planning agencies WLO (*Welvaart en Leefomgeving*, welfare and environment) scenarios (WLO 2006). Two scenario families were derived: climate change was framed as either 'rapid' or 'moderate' (consistent with a global mean temperature rise of 4 and 2 °C by 2100), and socio-economic development characterised as either 'growth' or 'contraction' (consistent with population and economic growth or stagnation) (see Fig. 3). The uncertainty range covered by the scenarios was deliberately constrained to create a frame appropriate for engineering and economic modelling connected to the development of a new national flood risk management and freshwater strategies. This example shows that methodological limits frequently underpin the framing of future socio-economic uncertainties in scenario-based analysis.

To integrate the KNMI and WLO scenarios, several steps were taken. First, the different target years in the underlying scenarios had to be made consistent. For this, the WLO scenarios of 2040 were extrapolated to 2050 assuming unchanged socio-economic outlooks (Bruggeman et al. 2011). For 2100, the WLO outlooks were defined in expert workshops with assumptions about economic and population growth as determining factors. Four indicators—economic growth, population growth, temperature and sea-level rise—were used to define extreme points for the two target years, 2050 and 2100. These four scenarios allowed modelling analyses of climate change impacts for vulnerable regions or sectors, in spite of presenting a partial uncertainty range, both from the perspective of climate change or vulnerability analysis. Practical application of the Delta Scenarios led to improved insight into the relative importance of climate change and socio-economic changes for regional development. For example, an assessment of the accessibility of the Rotterdam port area found that uncertainties about the volume of trade handled by Rotterdam are far more significant than uncertainties about river flow and sea-level rise (Meijers et al. 2012).

Bottom-up scenario approaches

Downscaling techniques can also be employed as a bottom-up approach, to the extent that new and relevant information, defined in cooperation with stakeholders, is used to produce 'tailored' regionally specific scenarios. During

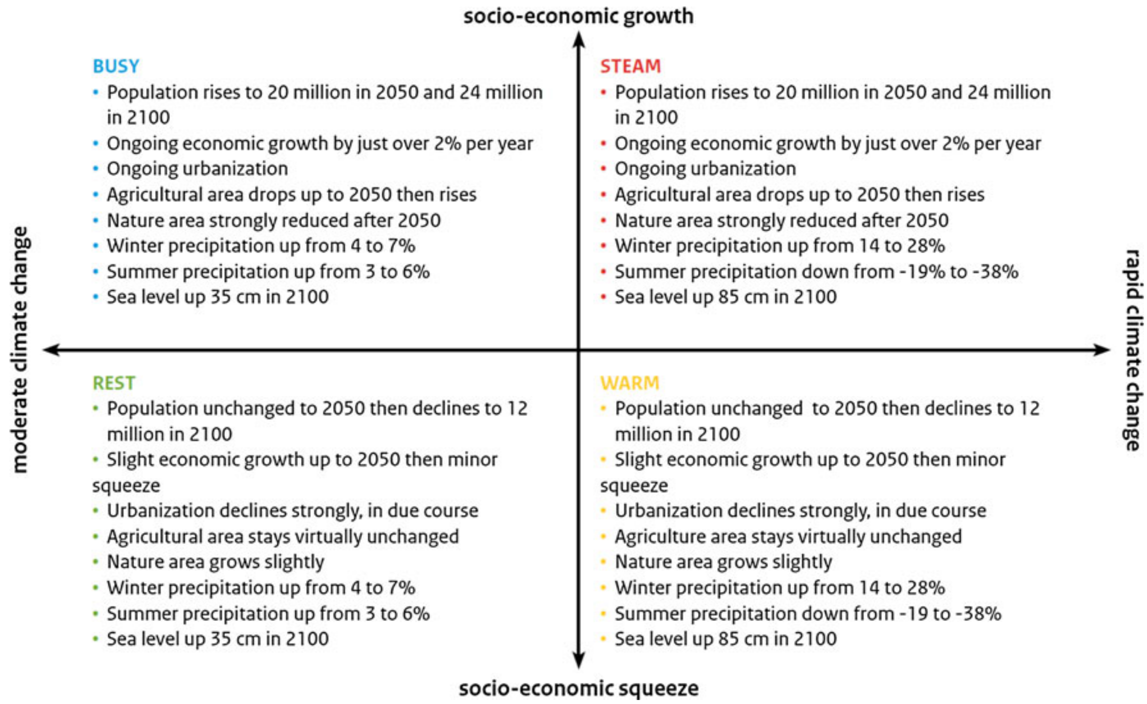

Fig. 3 Dutch Delta Scenarios (Deltacommissie 2008)

Table 1 User needs for climate data (*Source* Bessembinder et al. 2011)

	Wind energy	Sewage system	Coastal protection
Desired data	Wind speed	Precipitation extremes	Sea-level, wind speed and wind direction
Time resolution	Daily–monthly–annual	5–60 min	3-h annual
Desired time horizon	2015–2020	2050–2100	2050–2200

tailoring, regionalised data from climate models are adapted to the needs of specific groups of users (Gawith et al. 2009; Swart and Avelar 2011; EUMETNET 2010). User involvement in scenario development has become more important for the credibility, legitimacy and salience of outputs of scenario-driven assessments (Hulme and Dessai 2008). Tailoring requires interaction with stakeholders to specify the question that is most relevant to the user of the climate information (What kinds of outputs are relevant? At what scales is it needed? What are critical elements in the decision context where climate information plays a role? Which uncertainties are significant to the decision context?). Also, the tailoring process allows specification of alternatives where requested outputs cannot be provided, and for guidance in the interpretation of information and uncertainties.

In the Dutch Climate Changes Spatial Planning (CCSP) programme, tailoring climate information received considerable attention (Bessembinder et al. 2011; see Table 1), which took the KNMI'06 climate change scenarios for the Netherlands (Van den Hurk et al. 2007) as a point of departure. In these scenario tailoring projects, frames of climate modellers and stakeholders are gradually aligned. For instance, in a project developing adaptation strategies with provincial governments, a need was identified for a 'standard hydrological year' and guidance on its use (Bakker et al. 2011). This 'standard year approach' was preferred as it was faster and more flexible than a more conventional approach using full-scale 30-year model simulations. However, using a single sample year leads to rather limited information on changes in extremes and year-to-year variability (see Fig. 4).

Another example of stakeholder interaction relates to the wind energy sector. The electricity-power-producing company was interested in wind energy projections for the next 5–10 years, where a decline in wind energy yields over the North Sea during the last decades had caused a concern about near-term investment opportunities. The question was whether this decline is a manifestation of natural climate variability or whether a causal link exists with anthropogenic climate change. A statistical analysis of observations and model results (Bakker and van den Hurk

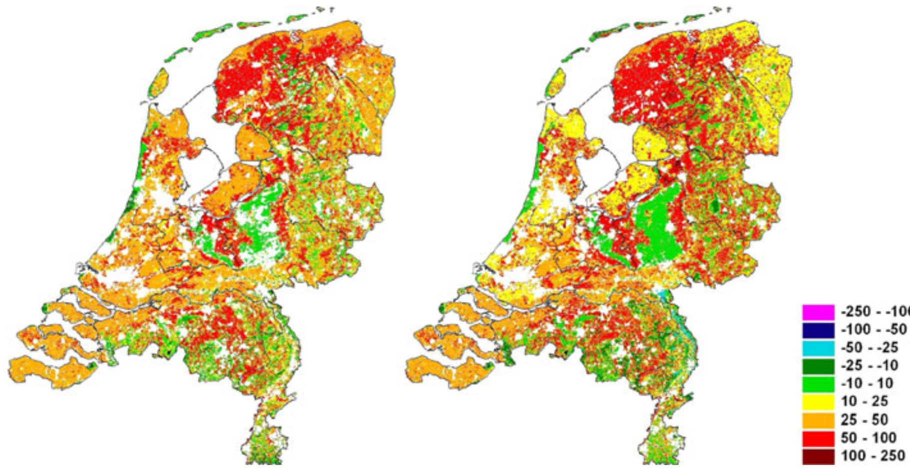

Fig. 4 Actual evaporation (mm) for Dutch regions with a 30-year simulation (*left*) and a simulation based on a 'standard year' (*Source* Bakker et al. 2009)

2012) led to the conclusion that model biases in long-term persistence of wind speed patterns did not allow a robust evidence-based answer to this question. A follow-up study was commissioned by the company, which focused on explaining wind energy yield trends. Here, it was concluded that trends in large-scale wind patterns were only partially responsible for the wind energy decline in the North Sea (Bakker et al. 2012). The information from this study helped the stakeholder in their trend attribution and served as underpinning data for future investments in wind energy.

Adaptation tipping point analysis

The adaptation tipping point (ATP) analysis is a bottom-up vulnerability analysis, which focuses on tipping points in local to regional adaptation strategies that threaten current management or policy objectives. Adaptation is viewed as a series of steps each responding to a stream of climate-induced constraints as they emerge through time. The analysis is framed in terms of management objectives and adaptation options available to the stakeholder and begins with an analysis of system vulnerability to climate variability and change. ATP analysis has been applied to Dutch water management, with regionalised outputs from climate projections as external forcing (Kwadijk et al. 2010). They found a number of ATPs for coastal flooding, river flooding and freshwater supplies. Such information, including uncertainties, was used to assess the feasibility, sequencing and costs of alternative adaptation options available now and in the future.

A surprising result of the analysis was that a key vulnerability of the Dutch water management system to future climate change may be associated with securing future freshwater supplies. Kwadijk et al. (2010) found that risks to freshwater supplies as a result of saline ingress related to sea-level rise, combined with low river discharge, appeared to be a risk that deserved as much attention as coastal or river flooding. Freshwater allocations currently permit a maximum allowable saline concentration of 250 mg/l. With a convergence of sea-level rise of 35 cm and low summer river flow along a key stretch of the Hollandsche IJssel River, strategically important water inlets would need to be blocked for considerable periods of time (rising from 0 to 76 days) as early as 2030, producing conditions which water managers felt could not be managed with currently available adaptive measures. A more fundamental re-design of freshwater supplied may therefore be called for.

Incident-driven scenarios

Extensions of the bottom-up approach that combine an assessment of 'event sequences' leading to significant exposure to catastrophic hazards associated with extreme events can also be envisaged. Extreme events are seen as representing critical risks and as stimuli for adaptive action (IPCC 2012b). Rather than seeing such events as an outcome of exogenous stressors of engineering systems, extreme events have come to be characterised as an outcome of interacting physical, institutional, organisational and cultural factors. The 2005 Katrina disaster in New Orleans, for instance, was an outcome of a combination of systematic under-investment in coastal defences, poor planning and corruption, which was exposed when an intense tropical cyclone hit the US coast (Congleton 2006).

Whether an event is framed as being extreme or a disaster also depends on the institutional and cultural context within which it unfolds. Disasters are situations in which existing provisions for risk management are exceeded and lead to unfamiliar and catastrophic hazards to people, property or ecosystems. They are typically an outcome of an accumulation of previously unknown or unanticipated sequences of circumstances, including unexpected interactions between different systems. Modelling event sequences leading to catastrophic risks is inherently difficult because they include unknown unknowns and because analysts and decision-makers have bounded rationality and specific frames for considering risk. If they had been able to conceive of an additional risk as being substantial, it is likely that this risk would have been taken into account in risk management strategies, all things being equal. To expand existing mental models (van Drunen et al. 2011), bottom-up scenario analysis needs to engage with complex and interacting chains of factors and events that could lead to catastrophic hazards.

A good place to start looking for relevant event sequences is near-disasters. For instance, in January 2012, a major rainfall event on already saturated soil led to problems in a northern Netherlands polder area. Surface water could not be discharged to the nearby North Sea due to a compounding storm surge. These events (high soil water content, heavy precipitation, storm surge) were not exceptional by themselves, but their coincidence in time and space led to a near-disaster (for similar examples see Kew et al. 2012). This event led to increased attention to the simultaneous occurrence of storm surge and heavy precipitation events. In principle, the degree to which compound events are causally related should be included in design criteria for water management infrastructure. A critical research issue concerns whether changes in climate conditions can lead to a systematic change of these compounding likelihoods (Leonard et al. 2013).

The scientific analysis needed to support decision-making in this context is different from traditional scenario analyses in a number of ways. First, the technical analysis is defined by the local conditions where region-specific vulnerability and resilience capacity play a dominant role. It needs to focus on the combined effects of events that can lead to major hazards. A clear description of the (physical and social) mechanisms leading to such event sequences is not only valuable for understanding possible dynamics or trends, but helps gain public support for the decision-making process. A transparent translation of multiple external weather or climate drivers to local socially framed impacts is a key element in such analysis.

The simulation of more-realistic representations of the biophysical aspects of extreme events using a model framework is improving over time as the realism of weather and climate models increases, and as they become increasingly integrated. This can help the framing of events as being plausible and therefore worth including in risk management planning (Hazeleger et al. submitted). However, it remains a difficult task to demonstrate the link between individual events and event sequences, and a given global climate change scenario. The individual event depicts a situation that can be considered to be plausible within a given climate scenario. But the event may be consistent with other climate scenarios, since it is a manifestation primarily of natural variability in the climate system interacting with social factors. In addition, determination of the typical return time of the event sequence (its 'rarity') is difficult to establish because of the large computer resources needed to generate adequate statistics. Thus, although an extreme event or event sequence is considered to be relevant from a vulnerability point of view, its link to top-down formulated scenarios and its likelihood of occurrence may be difficult to establish.

A focus on 'future weather' and extreme event sequences marks a significant change in the framing of both climate and socio-economic uncertainties in climate vulnerability assessments. First, climate variability feeding specific local vulnerabilities has become the focus of analysis. Second, the interaction between climate and socio-economic drivers in event sequences provides a way of making vulnerabilities more tangible for stakeholders. Third, the definition of potential event sequences is done in a process of co-learning with stakeholders; a process in which the frames of modellers and stakeholders can be further aligned.

Discussion: frames, decision contexts and scenario approaches

The diversification of scenario approaches for climate assessments is a response to the diversity of frames that exist among stakeholders situated in the highly diverse decision contexts. We have argued that a useful way of differentiating between scenario approaches (top-down, interactive or bottom-up) is to stratify them according to the scope and dynamics of decision contexts they serve (see Fig. 5). To support effectively the process of sense-making, understanding and learning, scenarios need to match with the frames of the stakeholder using the results. Frames are knowledge structures through which social actors organise and make sense of their life-worlds, creating the context for them to reason about climate change, and climate change-induced vulnerabilities and risks. Fundamental to this is a need to consider uncertainties, now and in the future. To do this, actors reason by similarity and by simulation. They draw on specific sources of tacit and codified knowledge, are situated within specific institutional contexts and relationships and are enacted through particular organisational routines. Intrinsic to decision contexts is also a set of assumptions or 'givens' that actors share and which define and stabilise their life-world. For some decision contexts, information needs will be local and fast, while others will be extensive and dominated by slow variables. Each decision context anticipates a degree of uncertainty and variability in internal and external conditions affecting the decision. While there will be some knowledge and experience about the resilience of a system, uncertainty about this resilience to specific stresses or extreme events and conditions will often exist.

The salience of information generated by scenario-based assessments depends on the match that is achieved with the scope, dynamics and uncertainties intrinsic to the frame of the actor, who is situated in a specific decision context (see Fig. 5). Scenario assessments extend the uncertainties that can be considered in a decision problem, whether this is climate uncertainty, socio-economic uncertainty or a combination of both. The framing of future uncertainties implicit in the scenario approach (whether a deterministic, exploratory or back-casting approach, for instance) will also define which uncertainties are included in an assessment. By choosing a scenario, the actor is therefore making a choice about which uncertainties are relevant or tractable to a given decision problem, and implicitly also a decision about which uncertainties are not. Part of the resistance to top-down scenarios is the feeling that the 'framing in' and the 'framing out' of uncertainties have been taken out of the hands of the decision-maker. Through interactive and tailoring processes, these choices are placed back into the hands of the decision-maker.

We may also see that the use of scenario-based assessments takes place in two steps. In the first—analytical—step, the aim will be to extend the uncertainties that are included in the problem framing and analysis. In a second—action—step, the aim will be to reduce the uncertainties again in order to be able to come to an adaptation action or strategy. Many of the uncertainties available through the scenario-based assessment will now be set aside. This too is a choice. Making a decision, including a decision to defer, involves the re-simplification of the decision problem by taking account only of significant uncertainties. A scenario-based assessment offers a menu of new and plausible uncertainties, but the decision-maker must choose to what extent these new uncertainties are fitted to the decision problem.

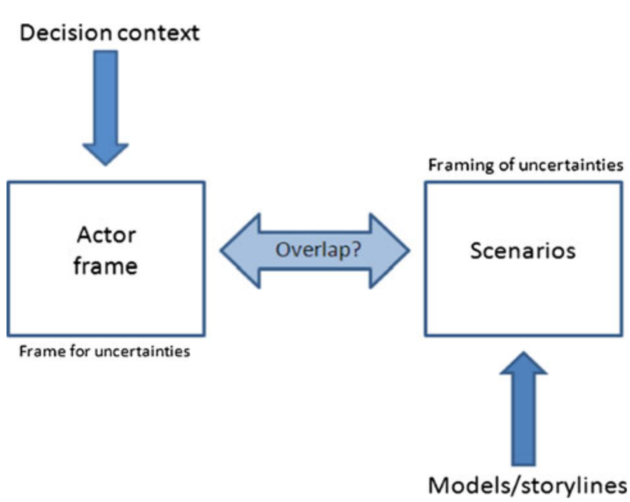

Fig. 5 Matching uncertainties in scenarios to actor framing of uncertainties

Conclusion: matching futures scenarios to the decision-making process

Analysis and decision-making under uncertainty can be strengthened by broadening the scope of uncertainties considered by using scenario tools. Different ways of representing climate change and risks need to be matched to actor frames and decision contexts. Such matching will not be achieved by working only on increasing the power of climate models in order to generate increasingly better downscaled climate information for users (cf. Lenton 2011). But nor can it be achieved by 'bracketing out' climate model outputs and focusing exclusively on the resilience and vulnerability of socio-technical systems at the local scale. Neither approach is capable of yielding the range of information and insight that decision-makers need and are able to handle.

In this paper, we have discussed different scenario approaches and decision contexts illustrated using a wide range of examples, varying from the classical, formal top-down approach of the IPCC process to locally specific, stakeholder-driven bottom-up analysis of vulnerability to compounding events. The examples discussed in the paper are summarised in Table 2. The collection illustrates the myriad of frames, scenario approaches and perceived roles of uncertainty.

To put the various frames and decision contexts into a general framework, we propose mapping the scenarios onto two dimensions (Fig. 6). The first dimension spans the spatial or institutional scale: from local to the national/global scale. The local scale refers, for instance, to regional vulnerable hot spots in a country, a specific sector, or an investment decision for maintaining local infrastructure. The scale of a decision context will determine the degree of spatial or temporal specificity relevant to the frame of the decision-maker. The second dimension varies across the range of conceptualisation: from top-down, generalised scenario techniques on one end of the range to incident-driven, tailor-made, bottom-up scenarios on the other. Each decision context can be matched with a particular scenario tool. These analyses are typically case-specific, and the mapping of relevant drivers and their coincidence require strong involvement of local experts and experience. Such assessments will need to combine and integrate uncertainties across a variety of both bio-physical and

Table 2 Examples used in this paper, the applied scenario approach and the description of how was dealt with frames and (perceptions of) uncertainty

Examples	How frames are addressed	Type of scenarios applied	Framing of uncertainty in scenarios	Ref. to fig. 6
IPCC RCP scenarios (scenarios 2.0) and Shared Socioeconomic Pathways (SSPs)	Aiming at multi-stakeholder, complex long-term decision contexts	Top-down inventory of socio-economic scenarios compiled by research community	Limited range of climate forcings considered, leaving room for multiple socio-economic narratives	Upper right corner
Dutch climate scenarios (KNMI'06)	Aiming at multi-stakeholder adaptation contexts; baseline for tailor-made (bottom-up) scenarios	Top-down inventory of relevant regional climate variables	Collection of scenarios constructed to illustrate range of possible futures, but perceived as full uncertainty range by some stakeholders	Upper right corner, with tailor-made scenarios to lower half of plane
Dutch delta scenarios	Started from research community, stakeholder participation increased during development process; general framework for locally specific adaptation decisions	Top-down inventory of relevant regional climate and socio-economic variables	Uncertainty range at local scale extends beyond dimensions covered by delta scenarios	Scenario framework: upper right corner; local and national interpretations: rest of plane
Dutch wind energy sector	Started as scientific study, but stakeholder involvement led to updated user-demanded study	Study of reliability of tools used to generate scenarios	For stakeholder: uncertainty about model bias less important than uncertainty about wind yield trends	Starting in upper right corner, moving to upper left corner
North Netherlands compound events	Bottom-up vulnerability approach, awareness triggered by weather event	Incident-driven scenarios applied	Uncertainty about return frequency of specific case is dominant motivator for study	Lower left corner
Revised hydrological standard year	Bottom-up vulnerability to extremes, mapped at national scale	Incident driven, adjusted to climate change impact	Uncertainty range limited by use of historic reference situation	Upper left corner
Adaptation tipping point analysis and Thames 2100 Study	Inventory of multiple boundary conditions relevant for decision context	Bottom-up vulnerability assessment of local sector	Uncertainty about climate variability only one of potential drivers behind changing vulnerability	Upper left corner

Also shown is the localisation of the example in the framework illustrated in Fig. 6

institutional or cultural factors in determining the vulnerability or resilience of a given system.

We have mapped the illustrative examples used in the paper in Fig. 6 and assessed them against the framing of uncertainty in each case in Table 2. Local vulnerability issues arising from specific historic incidents (such as a near-flooding in northern Netherlands in January 2012) can be found in the lower left corner of the Figure. In the top right, national water safety design is based on a formalised, top-down construction of scenarios (Haasnoot and Middelkoop 2012) involving a combination of general socio-economic trends and downscaled climate model outputs. It is worth remembering that these top-down assessments are usually initialised as a response to an extreme event which demonstrates the need to reconsider the resilience or vulnerability of a system. The Dutch 'Delta Plan' and the adaptation of coastal defences saw their inception after the major coastal flooding in 1953 and were updated after extreme river discharge levels in 1993 and 1995. A conventional top-down scenario framework is being developed for the new Delta Commission programmes (e.g. Bruggeman et al. 2011), providing boundary conditions to a range of regional hot spot analyses, which are approached via a bottom-up analysis.

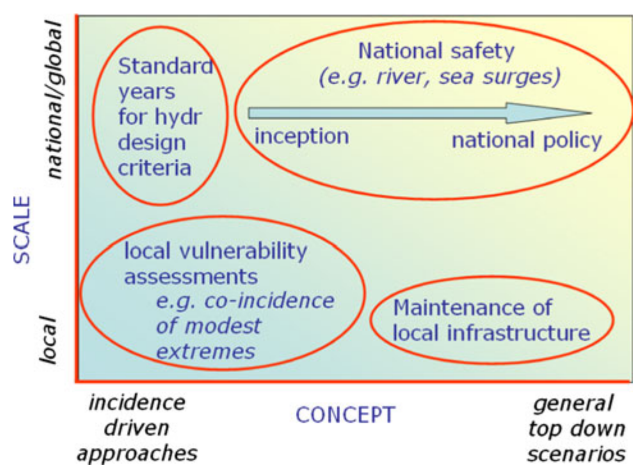

Fig. 6 Scenario approaches and their application

Off-diagonal examples can also be found. Building regulations, sewage design criteria and insurance law are decisions with a national scope, but often based on event-driven information about risk drivers. Historic rain events, for instance, form the basis of the design criteria of sewage systems, energy infrastructure or drought management. This reliance on historic incidents is often pragmatic: the impact of major climate/socio-economic drivers on the extremes that dominate the design criteria is often small or difficult to detect, while the impacts of these extremes are highly localised and difficult to generalise. An example at the other end of the diagram is where local decisions (like maintenance of the water management system by water boards or local authorities) are partially based on general scenarios. In the Netherlands, water boards need to demonstrate that they are compliant with the KNMI'06 scenarios for the next few decades while planning and reporting their infrastructure plans.

Are scientific developments in the area of scenario construction going in the right direction? With continuing investments in climate modelling and climate services, understanding of climate change will grow, producing improvements in the understanding of weather and climate dynamics at global and decadal scales, as well as local and seasonal scales. On the other hand, major uncertainties in climate projections over the medium and long term will persist. An increasing focus on seasonal and decadal forecasting for shorter-term projections holds promise, but the useful skill of these projections remains low (Van Oldenborgh et al. 2012). Parallel developments in improving methods and reducing the costs of incident-driven vulnerability assessments are also vital, and likely to generate improvements in the modelling of event sequences, in assessments of losses and gains and in cost-benefit assessment for adaptation options and pathways (Leonard et al. 2013; World Bank 2010). This will include the difficult question of how to deal with deep uncertainty about high consequence–low probability events. Here too, there is still much ground to be won. Highly diverse actor frames and decision-making contexts are a social fact. In all these cases, climate change impacts, vulnerability and resilience will be an outcome of complex interactions between bio-physical and socio-technical factors. Innovations in climate and socio-economic scenarios are most likely when they take the diverse frames of stakeholders seriously and offer a means of engaging with them.

Acknowledgments The research reported in this paper was funded under several projects of the Climate Changes Spatial Planning (KvR) programme (http://www.climateresearchnetherlands.nl/climatechangesspatialplanning). Comments from and discussions with Jaap Kwadijk, Jeroen Veraart, Alexander Bakker and (anonymous) reviewers and the editor have led to substantial improvement of this manuscript.

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