UNIVERSIDADE DE LISBOA
FACULDADE DE CIÊNCIAS
DEPARTAMENTO DE BIOLOGIA VEGETAL

CHANGING CLIMATE, CHANGING DECISIONS

UNDERSTANDING CLIMATE ADAPTATION DECISION-MAKING AND THE WAY SCIENCE SUPPORTS IT

DOUTORAMENTO EM CIÊNCIAS DO AMBIENTE

TIAGO CAPELA LOURENÇO

TESE ORIENTADA PELO PROFESSOR DOUTOR FILIPE DUARTE SANTOS E PELO PROFESSOR DOUTOR ROB SWART

2015

DOCUMENTO ESPECIALMENTE ELABORADO PARA A OBTENÇÃO DO GRAU DE DOUTOR

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PROGRAMA DOUTORAL EM ALTERAÇÕES CLIMÁTICAS E POLÍTICAS DE DESENVOLVIMENTO SUSTENTÁVEL

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The work presented in this dissertation was developed at the Departamento de Biologia Vegetal da Faculdade de Ciências da Universidade de Lisboa, with support from the cE3c/CCIAM - Centre for Ecology, Evolution and Environmental Changes / Climate Change Impacts Adaptation & Modelling research group and from Alterra - Wageningen University and Research Centre

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This dissertation should be referenced as: Capela Lourenço, T., 2015. Changing climate, changing decisions: Understanding climate adaptation decision-making and the way science supports it. PhD Thesis. Universidade de Lisboa. Portugal.

NOTA PRÉVIA

Na elaboração desta dissertação foram usados integralmente artigos científicos já publicados em revistas científicas indexadas e capítulos publicados em livro. De acordo com o previsto no n.º 2 do artigo 25º do Regulamento de Estudos Pós-Graduados da Universidade de Lisboa, publicado no Diário da República, 2ª série, n.º 57, de 23 de março de 2015, o candidato esclarece que participou na conceção, obtenção dos dados, análise e discussão dos resultados de todos os trabalhos apresentados, bem como na redação dos respetivos manuscritos.

A dissertação, por ser uma compilação de publicações internacionais, está redigida em inglês. O texto redigido em português foi escrito segundo o novo acordo ortográfico. Uma lista de referências é apresentada no final de cada capítulo em vez de no final da tese e devido a este formato poderá haver casos de duplicação de referências entre capítulos. Cada capítulo contém toda a informação de suporte a ele associada.

Lisboa, 6 de setembro de 2015,
Tiago Capela Lourenço

PRELIMINARY NOTE

The present dissertation includes original scientific papers already published in international indexed journals and chapters of a book. In accordance with the Article 25, No. 2, of the University of Lisbon Post-Graduate Studies Regulation (Diário da República, 2ª série, n.º 57, de 23 de março de 2015), the PhD candidate declares full participation in the scientific planning, data collection, analyses, discussion and writing of all manuscripts presented here.

The dissertation, being composed of a series of international publications, is written in English. The text in Portuguese was written according to the new Portuguese language spelling agreement. A reference list is given at the end of each chapter rather than at the end of the thesis. Due to this format, reference duplication across chapters may occur. Each chapter contains its own supporting information where required.

Lisbon, 6th september 2015,
Tiago Capela Lourenço

DEDICATÓRIA

Para ti, mãe

ACKNOWLEDGEMENTS

The list of people that want to thank is a long one. I feel privileged and honoured to have come across so many interesting colleagues and friends during this work that it becomes a difficult, but pleasant task, to show my appreciation to all. I'm bound to forget someone and for that my apologies.

First I would like to express my deepest gratitude to my main supervisor, Filipe Duarte Santos for his long-standing and active support. Since we've started working together, over a decade ago, I can only say that the amount of knowledge and inspiration I've received will last a lifetime. I thank him for the trust placed in me over this time, especially during the elaboration of this thesis, and for giving me enough encouragement and freedom to pursue my own ideas.

I would also like to show my deepest appreciation for my co-supervisor, Rob Swart, who I've had the privilege to work with in so many different contexts but that in all of them, without exception, never cessed to serve as an inspiration. His insights and constant support are one of the main reasons why this thesis even exists. I thank him for all the fruitful discussions in Lisbon and all around Europe. Those countless coffee breaks where I always heard a supportive word are simply priceless.

I wish to extend a very special thanks to Teresa Sales Luís, without whom this thesis would have never seen the light of day. I will be eternally grateful for all that she has done and for believing in me every step of the way. Her kind words and generous efforts have carried me in the final stages and made this thesis possible.

Thank you to all my colleagues at FCUL, whom I have and had the privilege to work with and discuss so much over the years, but better yet, that I can call friends. Many of those discussions gave me the inspiration to carry on and make this thesis a reality. Big thanks to, Hugo, Maria João, Elsa, Lecas, Mário, Nuno, Luís, Ana L, Raquel, Andreia, Gil, Pedro, Filipe, André, Ricardo, Vanja and to all the 'youngsters' that will keep CCIAM alive.

I would like to extend this appreciation to the FFCUL team that has supported and encourage me all the time, every time. I don't know where Lívia, Carla and Mafalda get the patience but I definitely appreciate it.

Special thank you to Angela, David and Gomes for proof-reading this thesis, among many other things, and especially for the friendship that makes me miss the office when I'm not there. They have given me more that I can ever repay and I never thought it would be possible to enjoy working with someone as I've enjoyed working with them. I would like also to thank my colleague and friend from the 'other office', Markus for all the hard work and fun we have had over so many years. I miss my workshops.

The work presented in this thesis would not be possible without the contributions of many. Ana, Annemarie and Robert are thanked for the publications that make a part of this thesis. This work is as much theirs as it is mine. Thank you to all that took part in the case studies and to Helen for the painstaking task that it was to handle them. Thank you Carin, Roger, Hans-Martin and Leendert for the co-editing and discussions.

Numerous colleagues over many countries have contributed to the thinking behind this thesis, with plenty of inspiration and fruitful experiences. I would like to thank in particular Andrea, Sabine, Martin and Jochen (Austria), Rob, Arthur, Florrie, Marit and Marjolein (The Netherlands), Suraje, Patrick, Martin and Paula (UK), Sergio, Sara and Silvia (Italy), Daniel, Marie, Erik and Maurice (France), Guillermo, Millan and Jose (Spain), Marianne, Richard, Michael, Adis, Henrik and Magnus (Sweden), Hans, Andre and Stephane (Denmark), Dave and Margaret (Ireland), Harri, Laura, Tim and Mirka (Finland), Wouter and Johan (Belgium), Kirsten and Inke (Germany), Richard M (US), Bob W (Australia), Sándor (Hungary), Staytcho (Bulgaria) and Paulo, Paulino, Eduardo, João D, Telmo, Cristina, Anabela, Dina, Ana M and João PN (Portugal). Several colleagues from the PDACPDS kept on inspiring me long after classes, so I would like to thank Pedro, Susana, Joana, Ricardo and Jorge, for the hours of good food and discussion.

Family and close friends have supported and put up with me over all these years. From Algarve to Lisbon and on both sides of the Tejo they continue to inspire me. I would like to thank Garrido, Lena, Guida, Teresa, Pedro I, Marlene I, Ricardo I, Joao D, Sofia, JP, Miguel, Kevin, Andre, Bruno P and Mariana; my southern-made buddies, Coelho, Cosquete, Hugo, Liliana, Ivo, Ana C, Fred, Filipe, Joao O, Pedro O, Melo, Paula and all the Ana(s); my surf mate of this recent years, Pedro A; my family around the corner, Bruno R, Marlene R, Luísa; and my god-kids, Maria Inês and Zé Pedro. I wish to thank all my different 'families' for their unconditional support. A special thanks to my god-parents Túlio, Ana Maria, Fernanda, Antonio and all at Minde; to Virgínia, Joao M, Lurdes, Zé and Catarina; and to my new-family, Maria Clara and all the Lacerda team.

Finally, I wish to thank Inês for sharing her life with me and for her unconditional support over all these years, and my father and grandmothers for having made me the person I am today. Hopefully this work can make them proud.

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RESUMO

Os mais recentes compromissos globais de mitigação das emissões de gases com efeito de estufa (GEE) não são tranquilizadores. Os esforços de redução de emissões de GEE, no âmbito da Convenção Quadro das Nações Unidas para as Alterações Climáticas, não registam avanços significativos. Apesar da tendência de diminuição das emissões de GEE no conjunto da União Europeia, as emissões globais têm continuado a aumentar, mesmo que a um ritmo mais lento. As alterações ambientais globais já observadas e as incertezas que rodeiam a evolução socioeconómica nas próximas décadas, geram desafios em relação à capacidade de muitas sociedades em lidar com o agravar de fenómenos climáticos extremos. Mesmo os países mais desenvolvidos demonstram ser frequentemente vulneráveis ao clima atual.

Estima-se que as concentrações de CO_2 na atmosfera terreste tenham aumentado em 40% desde o período pré-industrial, devido principalmente à queima de combustíveis fósseis e a alterações de usos do solo. As mais recentes evidências apontam para que a atual concentração atmosférica de GEE não tenha tido precedentes pelo menos nos últimos 800 mil anos. As variações na concentração atmosférica de GEE têm implicações para o clima e para a temperatura à superfície da terra, que são conhecidas e analisadas pela ciência desde o século XIX.

Maiores concentrações de GEE estão associadas a um aumento do forçamento radiativo no topo da atmosfera. Em relação a 1750, a variação do forçamento radiativo total é positiva, com a maior contribuição a vir do aumento da concentração atmosférica de CO_2. Isto significa um aumento da energia absorvida pelo sistema climático, e consequentemente, um aumento da temperatura à superfície da terra. Evidências recentes apontam para que, no período entre 1880-2012, o aumento da temperatura média global à superfície tenha sido de cerca de 0.85 [0.65 to 1.06] °C. Estima-se que é extremamente provável que as atividades antropogénicas sejam responsáveis por mais de metade do aumento observado entre 1951 e 2010. As observações de alterações do sistema climático têm-se acumulado, e apesar de dificuldades na sua atribuição, a influência humana nessas alterações está agora bem estabelecida. No entanto, e como em todos os sistemas complexos e não-determinísticos, alterações futuras são, por definição, incertas. Espera-se que a emissão continuada de GEE provoque um aumento adicional da temperatura média global e alterações variadas no sistema climático, que apenas uma substancial e sustentada redução de emissões poderia limitar. Cenários recentes projetam um aumento entre 0.3°C a 0.7°C para o período 2016-2035 e de 0.3°C a 4.8°C para o período 2081-2100, relativamente a 1986-2005; e uma subida do nível médio do mar que pode ser de 0.26 a 0.98 m em 2081-2100, devido à

expansão térmica e à perda de massa dos glaciares e das calotes polares. Não se espera que as alterações nos regimes de precipitação e no ciclo global da água sejam no sentido de uma uniformização. Salvo exceções regionais, espera-se que os contrastes entre as regiões húmidas e secas e entre as estações húmidas e secas venham a aumentar.

A temperatura média global à superfície é maioritariamente determinada pelas emissões cumulativas de GEE, pelo que a maioria destes aspetos deverá persistir durante o presente século e até para além, mesmo num cenário de completa suspensão das emissões. Este "compromisso" com as alterações climáticas é substancial, persistente e uma escala de séculos. Os impactos de anteriores alterações climáticas (naturais) estão bem registados ao longo da história, embora as suas consequências sejam muito variadas tanto para os sistemas naturais como para as sociedades humanas. Espera-se que futuras alterações (antropogénicas) como as que são projetadas, tenham igualmente impactos e implicações significativas. Os impactos relacionados com o clima que têm sido sistematicamente observados incluem, entre outros, alterações nos ecossistemas, disrupção da produção alimentar e da disponibilidade de água, danos em infraestruturas, e efeitos nocivos para a saúde humana e para o bem-estar.

Muitos sistemas naturais e humanos são sensíveis a alterações do clima, embora a sua vulnerabilidade seja dependente da exposição, localização, tempo e fatores não-climáticos variados. Uma vez que a vulnerabilidade e a exposição variam temporal e espacialmente, alterações nas características socioeconómicas têm uma influência significativa nas consequências associadas ao risco climático. A distribuição global deste risco é extremamente dependente do contexto, sendo que impactos benéficos são também esperados para diferentes regiões e setores. Os impactos e os riscos irão variar entre regiões e populações, sendo dependentes do sucesso das respostas a este desafio.

São geralmente considerados dois tipos de resposta, a mitigação (i.e. redução das emissões de GEE e/ou o seu sequestro a partir da atmosfera) e a adaptação (i.e. redução dos efeitos adversos e/ou o aproveitamento de oportunidade benéficas). A presente tese é exclusivamente sobre a segunda - a adaptação às alterações climáticas - e em particular sobre a tomada de decisões tendo em conta as incertezas associadas. A definição de adaptação adotada nesta tese é a que foi recentemente descrita pelo Painel Intergovernamental para as Alterações Climáticas (IPCC), no seu último relatório de avaliação (AR5). Adaptação é definida como o "processo de ajustamento ao clima atual ou projetado e aos seus efeitos. Em sistemas humanos, a adaptação procura moderar ou evitar danos e explorar oportunidades, e em alguns sistemas naturais a intervenção humana poderá facilitar este ajustamento".

Uma vez que as alterações climáticas (naturais ou antropogénicas) afetam as atividades humanas e se espera que o continuem a fazer ao longo dos próximos séculos, a adaptação às alterações climáticas coloca novos desafios a decisores em todo o mundo, uma vez que terão que ser tomadas decisões já, sobre como ajustar as mais variadas atividades, setores e sistemas, em múltiplas escalas espaciais e temporais. Estas decisões terão que ser sempre tomadas na presença de múltiplas incertezas. É portanto fundamental que, tanto os decisores como as comunidades que os apoiam nas suas decisões de adaptação (e.g. cientistas e consultores, entre outros) definam formas de promover a troca do conhecimento necessário sobre "porquê adaptar", mas também que desenvolvam os quadros conceptuais, métodos e ferramentas que permitam uma melhor compreensão de 'o que adaptar' e de 'como adaptar'. Esta tese debruça-se sobre questões relacionadas com decisões e processos de tomada de decisão em adaptação, e sobre a forma como a ciência apoia estes processos a lidar com a incerteza.

Esta tese é enquadrada por três perguntas de investigação. A primeira lida com a questão de a transdisciplinaridade ser uma condição fundamental para a tomada de decisões em adaptação. Conclui-se que apesar de poder ser uma condição necessária, a natureza transdisciplinar da investigação em adaptação não é suficiente para assegurar que "boas" ou "melhores" decisões de adaptação sejam tomadas em contextos reais. A investigação participativa, aplicada às questões da adaptação prática, deverá ser complementada com um tipo de conhecimento e desenvolvimento de conceitos de carácter disciplinar, e de alterações nos processos operacionais e/ou regulamentares associados a diferentes tipos de decisões.

A segunda questão procura contribuir para uma melhor compreensão do que são decisões de adaptação e de como estas se relacionam com o tratamento das incertezas. Através de uma seleção de casos de estudo que representam uma leque variado de setores e de processos de tomada de decisão reais, procurou-se analisar como é que as decisões de adaptação são tomadas, quais os seus requisitos e quais as implicações para os seus resultados, que decorrem da abordagem escolhida para lidar com as incertezas. Foram realizadas entrevistas com os decisores envolvidos e com os cientistas que os apoiaram, e os resultados demonstram a importância de considerar ambas as dimensões (decisão e apoio à decisão) e respetivos contextos de forma integrada. No entanto, sugere-se que o tratamento das incertezas não é uma garantia de ação prática, e que a atual perspetiva deste tipo de processos está ainda muito ligada a uma abordagem linear-racional, presente em ambas a dimensões.

Finalmente, uma terceira questão tenta identificar se os atuais quadros conceptuais utilizados para a tomada de decisão em adaptação estão (ou não) bem equipados para caracterizar, apoiar e

concretizar diferentes práticas de adaptação às alterações climáticas. No contexto desta tese, os quadros conceptuais que enquadram a adaptação, são definidos como um conjunto integrado de conceitos, perspetivas e abordagens metodológicas, que permitem apoiar todo o processo de tomada de decisão. É sugerido que este tipo de conceitos tem que necessariamente integrar todas as dimensões naturalmente presentes num processo de decisão em adaptação, nomeadamente, os objetivos da decisão, as atividades de apoio à decisão, a tomada de decisão e os seus resultados. Os atuais quadros conceptuais em adaptação têm sido propostos a partir de uma perspetiva científica e seguem uma abordagem racional relativamente à decisão em contexto de incerteza. Esta abordagem assume que na presença de informação e de métodos de apoio, as decisões de adaptação serão de facto tomadas. Esta perspetiva parece ser suficiente para lidar com decisões estratégicas que procuram melhorar a capacidade adaptativa. Por outro lado poderá não ser apropriada para decisões de carácter operacional, normalmente associadas a opções que diminuem a vulnerabilidade às alterações climáticas, devido à dificuldade de levar em linha de conta a incertezas associadas à decisão em adaptação.

Palavras-Chave: alterações climáticas, adaptação, transdisciplinaridade, processos de decisão, incerteza

ABSTRACT

The current pace of global mitigation efforts brings about growing concerns about climate change impacts. In turn, even in developed countries, most societies are often vulnerable to present day climate and will most likely see those vulnerabilities exacerbated by future climate trends and extremes, accentuating the need for a coherent response through adaptation efforts. Such efforts will always have to be developed in face of uncertainty. The deeply rooted uncertainties that underpin climate change adaptation as a scientific, political and societal endeavour will always be a part of adaptation decision-making processes. It is fundamental that decision-makers and scientific communities find common ground that allows to exchange the necessary knowledge on "why to adapt", but also to develop the required frameworks, methods and tools that sustain a clearer understanding of "what to adapt" and "how to adapt" under long-term, uncertain circumstances. This thesis is about climate adaptation decisions and decision-making processes, and how science supports and equips them to handle uncertainty. The assessment and conclusions presented in this thesis reflect research that was transdisciplinary in nature and that included working close to decision-makers in their real-life contexts. The main objective of this thesis is to enrich the understanding of how adaptation decision-making takes place in those contexts and how science can better support it in dealing with associated uncertainties. Three key research questions underpin this thesis. The first deals with the issue whether transdisciplinarity in adaptation research is a fundamental condition for practical adaptation decision-making. This thesis argues that although transdisciplinarity may be a necessary condition, it is not a sufficient one to assure that "good" or "better" real-life adaptation decisions are made. Participatory, practice-oriented research is of outmost importance, but it has to be complemented by a more fundamental inquiry and concept development from disciplinary sciences and with changes in the operational and/or normative standards associated with long-lasting decisions. Transdisciplinarity has been framed as a potential solution for the gap between knowledge production and practical adaptation action. However, a more fundamental change in the way adaptation decision-making processes are framed, one that goes beyond the simple assimilation of the perceived needs of decision-makers, may be required to bridge that challenge. The second question reflects the current gap in the understanding of what climate adaptation decisions are and how they relate to existing or perceived uncertainties. Using a set of selected case-studies spanning across a wide range of sectors and different real-life decisions, this thesis reviewed and analysed how adaptation decisions are being made in practice, their knowledge requirements, and the implications that dealing with uncertainty has regarding their outcomes. In order to consider all steps of the adaptation decision-making process, interviews were conducted with both decision-makers and those involved in supporting them via science and other activities. Results demonstrate the importance of considering both dimensions and respective contexts in dealing with uncertainty. However, results also suggest that uncertainty-management is not a guarantee of action, and that the current framing of adaptation decision-making is still very much tied to a rational-linear view, both from the policy and decision-making perspective, as in the science and decision-support standpoint. This leads to a third research question that aims to identify if current adaptation decision-making frameworks are well equipped to characterise, support adaptation and enhance adaptation action under uncertainty. In the context of this thesis, a decision-making framework is a holistic set of concepts, perspectives or approaches that support the entire adaptation decision-making process. This thesis argues that such frameworks should necessarily include and integrate all dimensions that naturally occur in an adaptation process namely, the decision-objectives, the decision-support, the decision-making and the respective decision-outcomes. Current frameworks have been mostly framed from a research and expert perspective that follows a rational approach to decision-making under uncertainty. Under such perspective, it is assumed that by providing information and decision-support practical adaptation decisions will be made. This appears to be sufficient to deal with strategic decisions that look into improving adaptive capacity, but seems no longer fit-for-purpose when it comes to operational decisions, the type generally required to advance vulnerability-reducing actions.

Keywords: climate change, adaptation, transdisciplinarity, decision-making, uncertainty

LIST OF ACRONYMS

AR4 - Fourth Assessment Report (of the IPCC)

AR5 - Fifth Assessment Report (of the IPCC)

BAU - Business as Usual

BM - Bayesian Methods

CAA - Climate Adaptation Atlas

CCIVA - Climate Change Impacts, Vulnerability and Adaptation

CCRA - Climate Change Risk Assessment (UK)

CIRCLE-2 - Climate Impact Research & Response Coordination for a Larger Europe (Project)

CMIP3 - Climate Model Intercomparison Project 3

DIVA - Dynamic Interactive Vulnerability Assessment model

DJF - December, January, February

DRR - Disaster Risk Reduction

EE - Expert Elicitation

EPP - Extended peer review

ERA-Net - European Research Area-Network

FP7 - European Commission 7th Framework Programme for Research and Development

GCM - General Circulation Model (also Global Climate Model)

GHG - Greenhouse gases

H2020 - Horizon 2020 European Commission Research and Innovation Programme

HadCM - Hadley Centre Coupled Model

IAM - Integrated Assessment Model

IMAGE - Integrated Model to Assess the Global Environment

IPCC - Intergovernmental Panel on Climate Change

JJA - June, July, August

JPI - Joint Programming Initiative

MAM - March, April, May

MC - Monte Carlo

M&E - Monitoring and Evaluation

NUSAP - Numeral, Unit, Spread, Assessment and Pedigree

PDF - Probability distribution function

PMME - Probabilistic multi-model ensemble

PPE - Perturbed Physics Ensemble

QA/QC - Quality assurance / Quality checklists

RCM - Regional Climate Model

RCP - Representative Concentration Pathways

RF - Radiate forcing

RRI - Responsible Research and Innovation

SA - Scenario Analysis

SENS - Sensitivity Analysis

SI - Stakeholder Involvement

SON - September, October, November

SRES - Special Report on Emissions Scenarios

SSH - Social Sciences and Humanities

SST - Sea Surface Temperatures

SWAT - Soil & Water Assessment Tool

TAR - Third Assessment Report (of the IPCC)

UKCIP - United Kingdom Climate Impacts Programme

UNFCCC - United National Framework Convention on Climate Change

WC/SS - Wild cards / Surprise scenarios.

WGI - Working Group One (of the IPCC)

WGII - Working Group Two (of the IPCC)

WGIII - Working Group Three (of the IPCC)

CHAPTER 1: CLIMATE ADAPTATION DECISION-MAKING UNDER UNCERTAINTY

This thesis is about climate adaptation decisions and decision-making processes, and how science supports and equips them to handle uncertainty. The assessment and conclusions presented reflect research that was transdisciplinary in nature and that included direct work with decision-makers in real-life contexts. The main objective of this thesis is to enrich the understanding of how adaptation (and adaptation-related) decision-making takes place in reality and how science can better support it in dealing with associated uncertainties. It aims at developing a general framework that provides a better appreciation of the entire adaptation decision-making process. The motivation for this work originates in the need to develop the way in which uncertain scientific and policy information allows societies to respond to changing climates. This thesis attempts to do that by better understanding what different types of decision-making processes need, rather than what different decision-makers demand, while acknowledging the role played by individual values and cultural norms. The application of this work is mainly targeted at decision-making processes in developed countries. However, it is expected that its application can be extended to other contexts, as long as this is explicitly acknowledged and that the framework is itself adapted to different settings.

This thesis aimed at reviewing, examining and evaluating three key research questions:

- Transdisciplinarity is generally considered as being fundamental for climate adaptation research and its application to decision-making. However, is it a sufficient condition to support 'good' or 'better' real-life adaptation decision-making processes?
- What are climate adaptation decisions and how are these currently handling associated uncertainties?
- Are current adaptation decision-making frameworks well equipped to characterise and support adaptation decisions and to enhance adaptation action under uncertainty?

This chapter provides a literature review and introduces key concepts such as climate change and variability (section 1.1), climate impacts and vulnerability (section 1.2), climate adaptation (section 1.3), uncertainty, risk and complexity (section 1.4), decision-relevant adaptation science (section 1.5), and adaptation decision-making under uncertainty (section 1.6). The final section of the chapter is about the research work that was carried out, and introduces the thesis rationale, structure and aims (section 1.7).

1.1. Climate change and variability

The earth's climate and its variations over time have an extraordinary importance for natural and human systems. Climate change is one of the most important and challenging issues of our time. Its effects span from the global to the local scale and from the societal to the individual level, with significant implications for generations to come. Climate is the long-term description of the earth's climate system and can change due to natural internal processes (internal variability), or because of external forcings (external variability). These can be of natural origin, such as solar cycles and volcanic eruptions, or anthropogenically driven, like persistent anthropogenic changes in the composition of the atmosphere or in land use.

Anthropogenic emissions of greenhouse gases (GHG) such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) have led to a significant rise in the atmospheric concentration of these gases, since the industrial revolution (circa 1750). Higher GHG concentrations change the chemical and physical properties of the atmosphere and are associated with a rise in the radiate forcing (RF) at the top of the atmosphere. Variations in the atmospheric concentrations of GHG have long-known implications for the earth's climate and for its surface temperatures (Arrhenius 1896).

The Fifth Assessment Report (AR5) from the Intergovernmental Panel on Climate Change (IPCC) points out that CO_2 concentrations have increased by 40% since pre-industrial times, primarily from fossil fuel emissions and from land use change (IPCC 2013). Evidence gathered in the AR5 suggests that current atmospheric concentrations of CO_2, CH_4, and N_2O are now at levels unprecedented in at least the last 800,000 years. In relation to 1750, the total RF is positive, with the largest contribution to that rise being the increase in the atmospheric concentration of CO_2. Estimates point that the total anthropogenic RF for 2011 relative to 1750 is 2.29 [1.13 to 3.33] Wm^{-2} and that it has increased more rapidly since 1970 than during prior decades. A positive RF leads to an uptake of energy by the climate system and consequently to a warming of the earth's surface. Over the period 1880-2012, the increase in the global averaged surface temperature (combined land and ocean) has been of 0.85 [0.65 to 1.06] °C (IPCC 2013). The IPCC concluded that it is extremely likely (probability of 95-100%) that more than half of the observed increase from 1951 to 2010 is of anthropogenic origin.

The combined evidence gathered by the IPCC suggests that it is virtually certain (probability of 99-100%) that human influence has warmed the global climate system. Despite this increase in global temperature, regional patterns exist and changes do not occur homogenously across the globe. The confidence about globally averaged (land areas) observed precipitation changes since 1901 is low before 1951 and medium afterwards. This reflects the more uncertain nature of precipitation patterns, which have a marked regional influence making global averaged data less reliable. Confidence in IPCC language, means a qualitatively expression of the type, amount, quality and consistency of the available evidence and the degree of agreement across it.

Although changes in many extreme weather and climate events have been observed at global and regional scales since about 1950, confidence in the evidence varies significantly, partly because of attribution issues. Regarding ocean warming it is virtually certain (probability of 99-100%) that the upper ocean (0-700 m) warmed from 1971 to 2010 and that it likely (probability of 66-100%) warmed between 1870s and 1971. There is high confidence that the rate of sea level rise since the mid-19th century has been larger than the mean rate during the previous two millennia with the mean sea level rising by 0.19 [0.17 to 0.21] m, over the period 1901 to 2010. Regarding the cryosphere there is high confidence that, for different time periods over the last two decades, both the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, and Arctic sea ice and Northern Hemisphere spring snow cover have continued to decrease in extent (IPCC 2013).

From a science perspective, the potential human influence on the climate system has been described for quite a long time (Broecker 1975). Observed evidences of changes in the climate system have mounted over decades and, despite attribution issues, humankind's influence upon the climate system seems now well established. Like all complex and non-deterministic phenomena, future changes in the climate system are by definition uncertain. In this regard, IPCC (2013) expects that the continued emissions of GHG will cause further warming and changes in all components of the climate system, and that only a substantial and sustained reduction of GHG emissions would limit climate change.

Using a new set of scenarios, termed Representative Concentration Pathways (RCP) (see Moss et al. 2010, Rogelj et al. 2012, Wayne 2013, Ebi et al. 2014), global mean surface temperature is projected to increase by 0.3°C to 0.7°C (2016-2035) and by 0.3°C to 4.8°C (2081-2100), relative to 1986-2005 (IPCC 2013). Under all RCP scenarios, global mean sea level is expected to continue rising during the 21st century due to increased ocean warming and loss of mass from glaciers and ice sheets. This rise will likely (probability of 66-100%) be in the range of 0.26 to 0.98 m for 2081-2100, relative to 1986-2005. Changes in precipitation and the global water cycle are not expected to become uniform. With regional exceptions, the contrasts in precipitation between wet and dry regions and between wet and dry seasons are expected to increase. Extreme precipitation events will very likely (probability of 90-100%) become more intense and more frequent by the end of the century, over mid-latitude continents and wet tropical regions (IPCC 2013).

Because global mean surface warming is mainly determined by past and cumulative emissions of CO_2 the majority of the aspects associated with climate change are expected to persist during the 21st century and beyond, even if emissions of CO_2 are stopped. This substantial multi-century climate change commitment is defined as the future change to which the climate system is committed by virtue of past or current forcings. A large fraction of anthropogenic climate change resulting from CO_2 emissions is irreversible on a multi-century to millennial time scale, except if a large net removal of CO_2 from the atmosphere over a long and sustained period would be promoted (IPCC 2013).

1.2. Climate change impacts and vulnerability

The impacts of past (natural) climate changes have been widely recorded throughout humankind's history, but their consequences have varied significantly for both natural systems and human societies (Diamond 2005). Future (anthropogenic) changes in climate such as the ones currently projected until the end of the century are expected to have significant impacts and implications across the globe. The IPCC Working Group Two (WGII) contribution to the AR5 points out that changes in climate over recent decades have already caused impacts on natural and human systems across continents and oceans (IPCC 2014a). While evidences of climate change impacts are stronger for natural systems, impacts on human systems attributed to climate change and distinguishable from other influences (e.g. changing social and economic factors) have been detected. The IPCC WGII AR5 links responses of natural and human systems to observed climate change, regardless of its cause (i.e. natural or anthropogenic), meaning that even for changes already observed, some uncertainty remains. Most of the reported impacts have been attributed to increase warming and/or changing precipitation patterns, with some degree of ocean acidification starting to emerge in the evidences (IPCC 2014a).

Observed impacts from climate-related extremes include alteration of ecosystems, disruption of food production and water supply, damage to infrastructure and settlements, morbidity and mortality, and consequences for mental health and human well-being. These extreme climate-related impacts are widespread across continents and types of systems including economic sectors, natural resources, ecosystems, livelihoods, and human health. Examples include droughts and floods in Africa, Australia, New Zealand and Europe, and extreme weather, including hurricanes, flooding, intense rainfall, intense heat and coastal storm events in North America (IPCC 2014a).

It is beyond the scope of this thesis to detail climate change impacts already observed worldwide. A depiction of main global patterns of impacts in recent decades, attributed to climate change since the fourth Assessment Report (i.e. AR4) in 2007, for a range of physical, biological and human managed systems, is presented in figure 1 (IPCC 2014a).

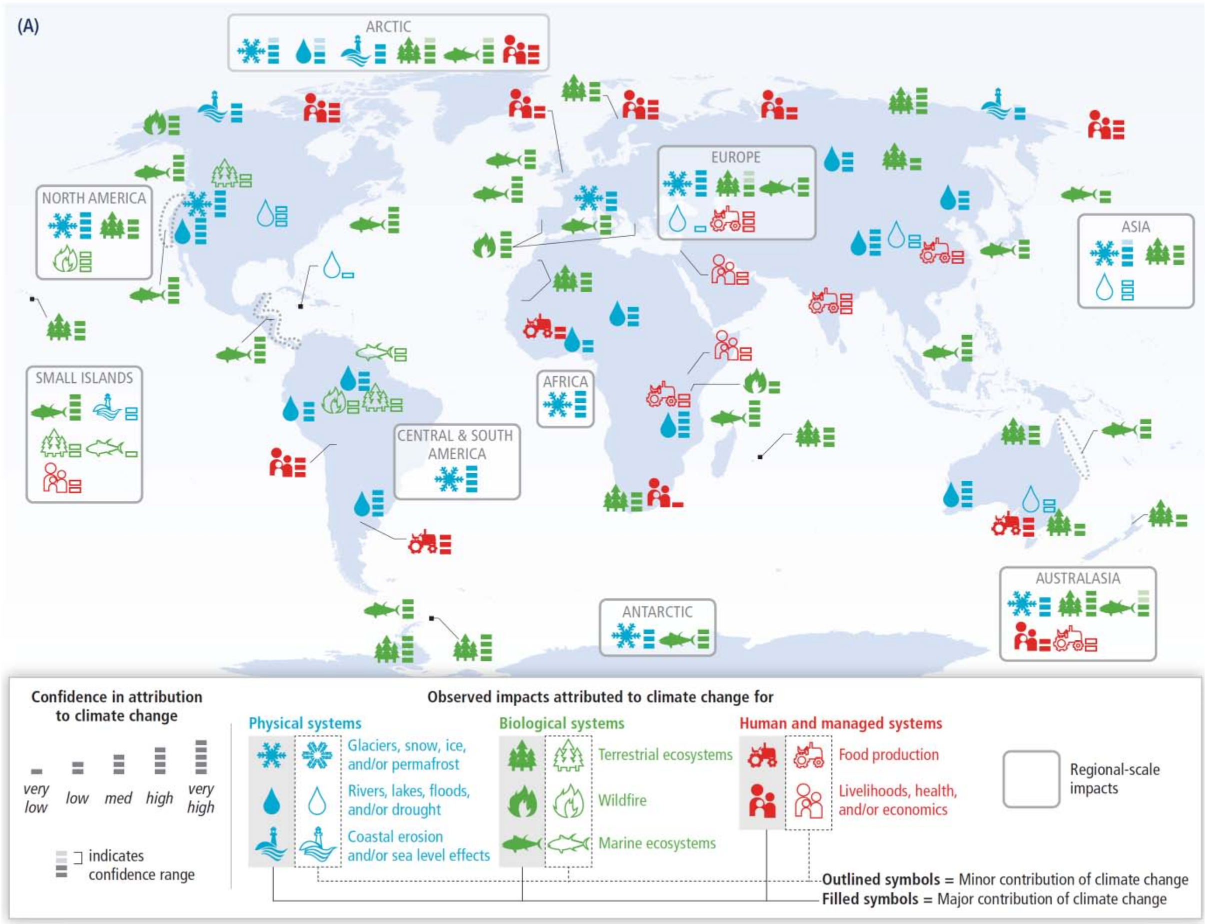

Figure 1 - Spread of impacts in a changing world. Global patterns of impacts in recent decades attributed to climate change, based on studies since the AR4, for a range of geographic scales. Symbols indicate categories of attributed impacts, the relative contribution of climate change (major or minor), and confidence in attribution [Source: IPCC 2014a].

Impacts attributed to climate change have been reported, with different degrees of confidence, for multiple sectors such as freshwater resources, terrestrial and freshwater ecosystems, coastal systems and low-lying areas, marine systems, food security and food production systems, urban and rural areas, key economic sectors and services, human health and human security (IPCC 2014a).

Many human and natural systems are sensitive to climate change, but their vulnerability is highly dependent of exposure, location, time, and non-climate factors such as social, economic, and environmental conditions. Because vulnerability and exposure vary over time and across geographic contexts, changes in poverty or socioeconomic status, ethnic composition, governance and age structure have had a significant influence on the consequences associated with climate-related hazards (IPCC 2014a). However, it has been pointed out that contested definitions and alternative approaches for describing regional vulnerabilities pose problems for interpreting vulnerability indicators, in particular at regional to local scales (IPCC 2014b).

Projected changes in global temperatures, precipitation patterns and other features of the climate system will bring about climate-related risks in most continents and oceans, for both natural and human or managed systems. Some beneficial impacts can also be expected. The worldwide distribution of risks and benefits is expected to be extremely context dependent (i.e. location and sensitivity) and therefore uncertain.

The likelihood of severe, pervasive, and irreversible impacts will increase with increasing magnitudes of warming, and while some global risks of climate change will be considerable at 1 or 2°C above preindustrial levels, there is the potential for high or even very high risks with global mean temperature increase of 4°C or more. It remains rather uncertain what levels of climate change may be sufficient to trigger tipping points. However, the IPCC expresses medium confidence that the risk associated with crossing multiple tipping points in the earth system increases with rising temperatures (IPCC 2014a).

Models and other studies project a multitude of global climate change-related impacts during and beyond this century, even for moderated warmings. Over the 21st century, the magnitude and severity of projected negative impacts may increasingly outweigh positive impacts. Major projected impacts (adverse and beneficial) and risks may include, among others (IPCC 2014a):

- increase in the fraction of global population experiencing water scarcity and affected by major river floods;
- significant reduction of renewable surface water and groundwater resources in most dry subtropical regions;
- increase of drought frequency in dry regions;
- increase of water resources at high latitudes;
- increase of the extinction risk of terrestrial and freshwater species;
- irreversible regional-scale changes in terrestrial and freshwater ecosystems;
- increase of coastal flooding and coastal erosion in coastal systems and low-lying areas;
- redistribution of global marine-species and reductions in marine-biodiversity;
- increase in ocean acidification impacts to marine ecosystems, especially polar ecosystems and coral reefs;
- increase inter-annual variability of crop yields in many regions and negative impacts in production of major crops in tropical and temperate regions, and geographical shifts in food production;
- amplification of risks for urban areas such as heat stress, extreme precipitation, inland and coastal flooding, landslides, air pollution, drought, and water scarcity;

- increase in rural impacts related to water availability and supply, food security, and agricultural incomes, including shifts in production areas of food and non-food crops;
- reduction in energy demand for heating and increase in energy demand for cooling in residential and commercial sectors;
- increase in losses and loss variability due to more severe and/or frequent extreme weather events and/or hazard types;
- exacerbation of already existing health problems, especially in developing countries with low income;
- greater likelihood of injury, disease, and death due to more intense heat waves and fires;
- increased likelihood of under-nutrition resulting from diminished food production in poorer regions;
- increase in the risks originated in food-, water- and vector-borne diseases;
- modest reductions in cold-related mortality and morbidity due to fewer cold extremes;
- increase in the displacement of people and human migrations, particularly in developing countries with low income;
- increase of the risks for human security, with the amplification of well-documented drivers (e.g. poverty and economic shocks) of violent conflicts, civil war and inter-group violence;
- slowdown of economic growth, making poverty reduction and assuring food security more difficult, in particular for developing countries.

Climate change impacts and risks will vary through time across regions and populations, being dependent on multiple factors and drivers including the extent of successful adaptation and mitigation, the two currently available responses to climate change.

Because there is a substantial multi-century climate change commitment, determined by past and current GHG emissions, a coherent response through adaptation is necessary, already now and for generations to come.

1.3. Climate adaptation

Mitigation of climate change relates to the reduction of GHG emissions and the sequestration of GHGs from the atmosphere. Adaptation to climate change refers to the successful reduction of the adverse effects of climate change and the enhancement of beneficial impacts. This thesis is exclusively about adaptation as a response to climate change. Links and trade-offs with mitigation are referred when appropriate.

The latest definition of adaptation by the IPCC AR5, which in turn followed the lead of the SREX report (IPCC 2012), is used in this thesis. It defines adaptation as *the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects* (IPCC 2014b).

Adaptation can be described in multiple ways but one of the most generically applied is relative to its intent or purposefulness (Smithers & Smit 1997; Eisenack & Stecker 2012; Noble et al. 2014). In this regard, a classical distinction is made between autonomous (or endogenous, built-in) referring to system responses that occur spontaneously, and deliberate policy decisions (or exogenous, planned, strategies) that require the imposition of formal adaptation frameworks (Carter et al. 1994; Feenstra et al. 1998; Smit et al. 2000; IPCC 2014b).

Another important feature of climate adaptation has to do with its ability to match or anticipate changes in climate patterns and respective impacts. Generally, such ability is respectively describe as being reactive (or ex-post) when it takes place after impacts are felt, or proactive (or ex-ante, anticipatory) when adaptation takes place before impacts and apparent (Smithers & Smit 1997; Klein & Maciver 1999; Mendelsohn 2000; Smit et al. 2000; Eisenack & Stecker 2012; Noble et al. 2014). Although useful, the above divisions are not completely straightforward even within the IPCC process. Purposeful adaptation is often interchangeably used to refer to actions that are carried out without external inputs (such as policies or resources) or actions that are reactive to experienced impacts (rather than proactive or consciously focused on addressing climate change) (Noble et al. 2014). Additionally, adaptation can be categorised according to how its objectives (or consequences) affect the fundamental characteristics of the system or process where it takes place (Smit et al. 2000). Adaptation can be incremental, when the central aim is to maintain the essence and integrity of a system or process at a given scale (e.g. maintain existing technological, institutional, values and governance arrangements). On the other hand, it can be transformational, when it seeks to change the fundamental attributes of a system in response to climate and its effects (Kates et al. 2012; O'Brien 2012; Wise et al. 2014; Noble et al. 2014).

Besides the three characteristics named above - purposefulness, timing and effect - Füssel (2007) also considered the planning horizon, the format and the involved actors as part of the dimensions that may be used to define and characterize (planned) adaptation. Walker et al. (2003) argue that understanding the impacts and benefits that result from present-day (i.e. observed) variability in climate is important in helping to reduce uncertainty surrounding the consequences of future climate change. Several studies have argued that any system that is poorly adapted to current climate variability is unlikely to be well adapted to future climate change (Burton 1997; Willows & Connell 2003; Adger et al. 2009; Burton 2009; Moser & Ekstrom 2010; DEFRA 2012; UKCIP 2013; Fankhauser & McDermott 2014). This notion is often referred to as (or part of) an 'adaptation deficit' in developing countries (Burton 2009, Moser et al. 2010, Fankhauser et al. 2014). Burton (1997) argued that improved adaptation to current climate is a step in the preparation for longer-term climate change.

Adaptation as a behavioural adjustment to changing climate conditions has occurred in the past. It is made up of actions that span across society, including individuals, groups and governments (Adger et al. 2005; Adger et al. 2007). Adaptation can include building adaptive capacity - increase in the ability of societies and/or individuals to adapt to changes - and/or implementing adaptation decisions - using those capacities and transforming them into action (Adger et al. 2005; Tompkins et al. 2010). Adaptation can be seen as a continuous stream of activities (including research), actions and attitudes that inform decisions about all aspects of life (Tompkins et al. 2010). Such adaptations can include both public and private sector changes. Individual and organisational actions are usually constrained by institutional processes such as regulations, laws, property rights and social norms (Adger et al. 2005; Adger et al. 2007), as these shape and influence the range of choices available to society (Jones et al. 2014). Demography, cultural and economic aspects, available technologies and capital as well as social conventions, psychology, language and ethics are known to influence adaptation (Adger et al. 2005, Jones et al. 2014).

There has been, for some time now, considerable debate about the barriers, constrains and limits to adaptation and its effectiveness. Common barriers include the public nature of valued goods, failures in collective decision-making, and uncertainties in available information (Tompkins et al. 2010). Detecting and defining problems, using information, and developing, assessing, selecting, implementing, evaluating and monitoring options can also represent significant barriers. Legitimacy, leadership, resources, communication issues, and values and beliefs have also been pointed out as potential limitations to adaptation (Moser et al. 2010). Other constrains may include necessary but missing actors or means, and complex actor relationships (Eisenack & Stecker 2012). Stafford Smith et al. (2011) describes a variety of psychological, social and institutional barriers for adaptation in a 4°C world, which are exacerbated by deep uncertainties and long timeframes. These include cognitive capabilities, affective systems, organisational processes, governance structure and institutions.

Hulme et al. (2007) and the Australian Government's Productivity Commission (Productivity Commission 2012) have broadly mapped the barriers and limits to adaptation by clustering them into policy, regulatory, social and behavioural (including cognitive) limitations. Although acknowledging that the focus is on market-economy based systems, the report by the Productivity Commission (2012) further defines market failures, governance and institutional barriers, path dependency and inadequate adaptive capacity as potential constrains for (successful) adaptation in Australia.

The concept of barriers and limits to adaptation has been widely used in national and sectoral studies across the world, for different scales and sectors and in both developed and developing contexts. Institutionally framed adaptation decisions are taking place across multi-level governance systems. This is a potential barrier for successful adaptation because of the need to manage local decisions for global problems through effective governance integration (Jones et al. 2014). Lorenzoni et al. (2007) looked into how the UK public perceive barriers in engaging with climate change. Jantarasami et al. (2010) studied the perceptions of managers of National Parks and Forests in the United States, regarding internal and external institutional barriers to adaptation. Burch (2010) analysed the role of barriers enablers of action for climate change in three municipal case studies in Canadian British Columbia. Measham et al. (2011) looked into constrains for adaptation municipal planning in Australia. Huang et al. (2011) provided a review and overview of the constraints and barriers to public health adaptation. Jones & Boyd (2011) analysed social barriers to adaptation in two case studies from Western Nepal. Finally, Matasci et al. (2013) used the concept to address the Swiss Alpine tourism sector and its stakeholders.

The application of the concept of limits and barriers to adaptation has been challenged on various grounds, especially if extrapolated across societies and contexts, For example, Adger et al. (2009) argue that the limits to adaptation are in fact, societally endogenous and therefore contingent on ethics, knowledge, attitudes towards risk and culture, thus making them mutable and subjective over time. For the authors this would mean that the limits are intrinsically connected to the respective adaptation objectives rather than with physical thresholds or even uncertainties in knowledge. Dessai et al. (2009) examined the implicit argument that effective adaptation is limited by the ability to provide decision-makers with accurate and increasingly precise assessments and predictions of future climate change. The authors concluded that the epistemological implications of such argument should not be seen as a limit to adaptation and that, instead, further importance should be placed in understanding the vulnerability of climate-related decisions to large and irreducible uncertainties. Despite the recognizable interest of context and scale in adapting to climate change, the widely used operative approach of identifying and cataloguing different barriers and then discussing the multiple ways of overcoming them has been contested by Biesbroek et al. (2015). The authors point out that, assuming that in the absence of barriers, socio-political systems would automatically adjust to changes, reduces the complexities of collective decision-making to simple input–output models, thus missing internal dynamics and processes. Such 'barrier thinking' usually blames failures in addressing climate change risks on factors such as lack of resources, lack of knowledge and/or lack of will. The authors suggest that this rationale should be abandoned, replacing questions of 'if' and 'which' barriers to deal with, by more analytical questions as to 'why' and 'how' these barriers emerge (Biesbroek et al. 2013; Biesbroek et al. 2015).

Adaptation as a response to climate change is recognized as a relevant science and policy issue across scales and sectors. However, defining what constitutes successful adaptation is a complex and difficult task. Adger et al. (2005) argue that if adaptation is relevant and impacts are already occurring, then it should also be possible to observe adaptation in contemporary societies. The authors add that the characterization and measurement of successful or effective adaptation depends on the temporal and spatial scale of implementation and on the criteria used to evaluate it against proposed objectives. Criteria such as efficiency effectiveness, equity and legitimacy are starting to be analysed (de Bruin et al. 2009) but remain context specific and are often contested because of competing values, since one stated objective may impose externalities on others, adaptation-related or otherwise (Adger et al. 2005). Striking a correct balance across success criteria is thus essential to evaluate current and future adaptation decisions and related actions. Doria et al. (2009) suggest that a better understanding of what defines successful adaptation is still rather under-researched. On the other hand, Dovers (2009) points out that there is already a well-known suit of options, often developed for other reasons than adaptation, which provide societies with a substantial advance in adaptive capacity and a basis for further development.

In fact, accumulated evidence over recent years seems to suggest that adaptation is already happening across Europe and the world (Adger et al. 2007; Biesbroek et al. 2010; Ford & Berrang-Ford 2011a; EEA 2012; CIRCLE-2 2013; EEA 2013; Hanger et al. 2013; Noble et al. 2014; EEA 2014, IPCC 2014b). The IPCC suggests that adaptation experience is already accumulating across regions and within communities, in both the public and private sector, with governments starting to develop adaptation plans and policies and integrating climate-change considerations at various levels. However, whether reported adaptation activities are simply individual actions, or if the observed adjustments to perceived changes are part of a more global (societal) transition towards better-adapted societies, remains to be verified (Tompkins et al. 2010). Recent attempts to provide a systematic tracking and profiling of the evolution of adaptation suggest that current adaptation planning is under-developed, of an ad-hoc nature at best, and much more centred in capacity building than in the delivery of practical vulnerability-reducing actions (Berrang-Ford et al. 2011; Ford et al. 2011; Jones et al. 2014).

For example, Arnell (2010) suggests that there are very few published examples or case studies of how adaptation to climate change is actually being delivered. Berrang-Ford et al. (2014) argues that the global distribution of (English-language) adaptation reports is highly inequitable and mostly focused on theoretical considerations of how systems may or can adapt, rather than how adaptation is taking place. In developed nations - where one would expect higher levels of planned adaptation taking place - Ford & Berrang-Ford 2011a found limited evidence of adaptation action, with reported interventions focusing typically in sectors already sensitive to climate impacts, most commonly at the municipal level and facilitated by higher-level government interventions, and with responses of a typical institutional nature. Practical descriptions of how adaptation takes place in real-life settings are slowly emerging (see EEA 2012, CIRCLE-2 2013) but remain the exception rather than the norm.

More recent attempts in understanding how adaptation is taking place around the world seem to confirm that adaptation at the national level is limited in developing countries, presumably because of poor governance, or because adaptation may be occurring within other jurisdictions (e.g. municipal, regional, civil society) (Berrang-Ford et al. 2014). The authors further highlight the critical importance of institutional capacity and governance settings for national-level adaptation. Such findings are in line with previous propositions from the literature, regarding the crucial implications of governance settings for adaptation at both national and lower-level scales (Brooks et al. 2005; Diaz & Rojas 2006; Urwin & Jordan 2008; Mickwitz et al. 2009; Swart et al. 2009; Biesbroek et al. 2010; Juhola et al. 2011; Bauer et al. 2012). Effective governance thus seems an important factor for adaptation. Case studies around the world have shown that institutions and organisational culture affects the use of information (Kirchhoff et al. 2013). Legal and regulatory frameworks have been pointed as important institutional components of the overall (climate) governance because they will be challenged by the pervasive nature of climate risks (Jones et al. 2014).

1.4. Uncertainty, risk and complexity

Because global climate change already influences activities and livelihoods across the world and will foreseeable continue to do so for centuries to come, decisions have to be made regarding how to adjust and improve the coping capacity of human and natural systems. Adapting to climate change poses new challenges to decision-makers around the world, since real-life choices will have to be made now (and over the next decades) about how to adapt activities, systems and sectors, at all geographical scales.

The commonplace perception that there is an urgent need to mitigate globally and adapt locally is bounded by the notion advanced by the IPCC (2014a) that adaptation and mitigation choices made in the near term, will affect the risks of climate change throughout the 21st century. Responding to climate-related risks involves making decisions in a changing world, while addressing continued uncertainty about the severity and timing of impacts, and the limits to the effectiveness of adaptation. Uncertainties about current and future vulnerability, exposure, and the responses of a growing set of interlinked human and natural systems are (and will remain) large. This creates additional challenges due to the number of interacting social, economic and cultural factors, which have been incompletely considered to date (IPCC 2014a).

Decision-makers looking to analyse, design, implement and monitor adaptation strategies, plans, options and measures will always face uncertainty relative to both current and future climate, about how climate is and will change, and about what are the “best” or “desired” choices to respond via planned adjustments. Those providing science-based knowledge in support of such decisions will also always need to deal with uncertainty, as it is considered as being an integral (and indissociable) part of science. Uncertainty is not exclusive to climate change research (Moss & Schneider 2000) and many other scientific fields are confronted with a wide range of uncertainties in their work, in turn influencing other areas of importance to adaptation decision-making.

If on one hand scientific uncertainty cannot be simply banished or controlled by routine (Funtowicz & Ravetz 1990) on the other, science-based (or -supported) adaptation decisions still have to be made. When predictive certainty is elusive and probabilistic information (or less than that) is all that is available, decision-making can benefit from “uncertainty management” frameworks (Hansson 2005) that try to avoid the use of “magic numbers” (Funtowicz & Ravetz 1990), by acknowledging that a range of uncertainties does in fact exist. Moss and Schneider (2000) noted that while ‘science’ itself strives for objective empirical information, ‘science for policy’ must be recognised as a different enterprise since it involves being responsive to policy-maker's requirements for expert judgement, at a particular time and given the available information, even if some of those judgements involve considerable subjectivity.

In this regard, (Funtowicz & Ravetz 1990) describe uncertainty as a situation of inadequate information relatively to its function as an input to decision-making, and divides it into three sorts namely, inexactness (usually expressed in conditional error information), unreliability (described in terms of confidence) and border with ignorance (all gaps of knowledge not included in the previous sorts).

The latest IPCC AR5 definition of uncertainty describes it as "*a state of incomplete knowledge that can result from a lack of information or from disagreement about what is known or even knowable. It may have many types of sources, from imprecision in the data to ambiguously defined concepts or terminology, or uncertain projections of human behaviour. Uncertainty can therefore be represented by quantitative measures (e.g. a probability density function) or by qualitative statements (e.g. reflecting the judgment of a team of experts)*" (IPCC 2014a).

Using a somewhat different perspective, uncertainty is conceptually described by Walker et al. (2003) as being "*any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system*". The authors outlined three dimensions of uncertainty namely, their level (were in the knowledge spectrum), location (where it manifests in, e.g., a model) and nature (the underlying cause of uncertainty). Uncertainties can manifest in various steps of a science-informed adaptation decision-making process and be relative to both decision-making itself and/or the activities supporting it. Multiple typologies have been described for uncertainty and for how it can influence the underlying knowledge of a decision-making process. It is beyond the scope of this introduction to go into a detailed description about the location and the nature of uncertainty.

Table 1 provides a generic outline of the main uncertainty typologies as they appear in the literature. For relevant discussions about these (and other) typologies and it applications to science and climate change decisions-making, see Funtowicz & Ravetz (1990), van der Sluijs et al. (2003), Walker et al. (2003), Hansson (2005), Dessai et al. (2007), Stainforth et al. (2007), CPB-PBL-Rand (2008), CCSP (2009) and Curry & Webster (2011).

Table 1 - Main typologies of uncertainty [Compiled by the author after van der Sluijs et al. (2003), Walker et al. (2003), Dessai et al. (2007), CCSP (2009) and Kwakkel et al. (2010)]

Uncertainty typology	Characteristics
Level	**Statistical:** aspects of uncertainty that can be described in statistical terms (e.g. measurement uncertainty due to sampling error, inaccuracy or imprecision in measurements)
	Scenario: implies that it is not possible to formulate the probability of occurrence of one or more particular outcomes
	Recognised ignorance: fundamental uncertainty about the mechanisms under analysis and a weak scientific basis for developing scenarios; Can be further divided into reducible ignorance that may be resolved by conducting further research, and irreducible ignorance (or indeterminacy) implying that research cannot improve knowledge
	Total ignorance: implies deeper level of uncertainty, where we do not even know what we do not know ("unknown unknowns")
Location	**Context:** identification of the boundaries of the system to be assessed (e.g. portions of the real world that are considered or left out of a model)
	Model (structure): associated with the conceptual model and the form of the relationships between the variables chosen to represent the system; **Model (technical):** associated the computer implementation of a model
	Inputs: associated with the input data sets used to describe the reference system (e.g. land-use maps, infrastructures) and with external driving forces that influence the system and its performance (e.g. policy or economic variables).
	Parameters: associated with the data and methods used to calibrate the model parameters
	Model outcome (also referred as prediction error): accumulated uncertainty caused by the uncertainties in all locations, propagated through the model and evidenced in the simulated outcomes
Nature	**Epistemic:** associated with imperfections of knowledge, which may be reduced by further research and empirical investigation
	Ontic (often referred to as variability or aleatory): associated with the inherent variability or randomness of nature and human behaviour

Walker et al. (2003) proposes a logical scale of different 'levels' of uncertainty ranging from an ideal of determinism to full indeterminacy, marking the limit before total (or unrecognized) ignorance (also termed the 'unknown unknowns'). In between these limits, the authors describe a continuous progression of uncertainty levels including statistical uncertainty (adequately described by known probabilities), scenario uncertainty (range of possible outcomes with unknown probabilities) and recognized ignorance (both the range of outcomes and probabilities are unknown because the mechanisms and functional relationships leading to them are poorly understood). Such a description is reinforced by Hansson (2005) that provides a scale of knowledge situations for decision problems extending between certainty (deterministic knowledge), risk (complete probabilistic knowledge), uncertainty (partial probabilistic knowledge) and ignorance (no probabilistic knowledge). This description was later on adopted by Warmink et al. (2010) that applied it in the identification and classification of uncertainties using both a hydraulic and a fuzzy-set model as case studies.

Refsgaard et al. (2007) define uncertainty as "*the degree of confidence a person has about the specific outcome of an event or action*". The authors point out that this subjective interpretation on "the degree of confidence that a decision-maker has about possible outcomes and/or probabilities of these outcomes" is specifically aimed at model applications for water management. Reasons behind this lack of confidence might include "a judgement of the information as incomplete, blurred, inaccurate, unreliable, inconclusive, or potentially false".

Both Refsgaard et al. (2007) and Warmink et al. (2010) apply the concept of uncertainty to environmental modelling processes. Walker et al. (2003) focuses more generally on the point of view of those providing model-based knowledge in support of policy decision-making and Hansson (2005) emphasis is more on the general underlying decision theory. The literature on uncertainty and its relation to climate change and environmental decision-making has been growing. For example, the Walker et al. (2003) framework has been applied to many domains, and has undergone multiple changes that resulted in a proliferation of uncertainty frameworks, a situation that counters the proposed objectives (i.e. integration and harmonization) of the original framework. For an extensive review of these applications and respective changes to the original framework, see Kwakkel et al. (2010).

The Walker et al. (2003) framework explicitly focused on the modeller's perspective about uncertainty, avoiding the perspective of decision-makers. Over time, domain specific discussions around terms that are used as synonymous for uncertainty, such as ignorance, doubt, unsureness, risk, ambiguity, imprecision or randomness, gained relevance (Kwakkel et al. 2010). Additionally, a shift toward stronger decision-oriented focus and the perception of uncertainty (e.g. framing), lead to a revision of the level and the nature dimensions of uncertainty. This revision has been put forward by Kwakkel et al. (2010) in the form of a synthesised framework. In this revised framework, not only the level dimension is reconceptualised (e.g. by including 'medium' and 'deep' uncertainty in-between statistical and recognised ignorance), but also ambiguity is included as a type of uncertainty nature. For an extensive review on issues related with the communication of different aspects of uncertainty, see Kloprogge et al. (2007). For additional considerations about the implications of the levels, nature and location of uncertainty in practical adaptation decision-making, see Capela Lourenço et al. (2014).

For some time now, the terms ‘cascade’ or ‘explosion’ of uncertainty have been applied to climate change science and policymaking because of the pervasive and accumulating nature of uncertainty that arises when conducting climate change assessments for the purposes of making decisions (New et al. 2000; IPCC 2001; Dessai & Hulme 2007; Wilby & Dessai 2010; Pidgeon & Fischhoff 2011). These uncertainties accumulate at each step going from emission scenarios, to carbon cycle response, to global climate responses, to regional climate scenarios and finally to the analysis of vulnerabilities and the production of a range of possible local impacts (IPCC 2001; Dessai & Hulme 2007; Pidgeon & Fischhoff 2011). For example, there are uncertainties associated with future emissions of GHG and aerosols, uncertainties about the global and local responses of the climate system (including their magnitude, timing and spatial distribution, sometimes with opposite signs), uncertainties associated with downscaling methods, biophysical impact models and the spatial and temporal distributions of all sorts of impacts and vulnerabilities (Dessai et al. 2007). There are also uncertainties associated with the past, present and future state of local environments and with how they will respond to climate change. Finally, there are uncertainties associated with the assessment and evaluation of adaptation options and measures, and with decision-makers preferences, values and objectives, amongst a multitude of other societal influences.

Since all adaptation-related decisions (or decision-making processes) are affected by uncertainty and focused on valued objectives, they can be considered as decisions involving risk (Jones et al. 2014). Risk steaming from the potential impacts of climate change arises not only from how the future is described, but also from the uncertainty, actual or perceived, surrounding that description (Eiser et al. 2012). These authors contend that, it is only because there is the need to act under conditions of uncertainty that the concept of risk matters altogether. Willows & Connell (2003) described uncertainty as the quality of knowledge about risk, in other words, when there is a lack of, or imprecision in the knowledge concerning the outcomes, e.g., when the probabilities and magnitude of either the hazards and/or associated consequences are uncertain. In fact, even when there is a precise knowledge of these elements, uncertainty may still exist since their outcomes are probabilistically in nature.

Complexity is another important attribute in framing and implementing adaptation decision-making processes. In particular, when complex environments interact with conflicting values such as the ones involved in climate change, the resulting challenges can be described as ‘wicked’ problems. These harbour - amongst other issues such as diffuse boundaries, different framing by different groups and individuals, and unclear solutions - large and ‘deep’ scientific uncertainties that are not easy to quantify (Jones et al. 2014). Complexity has made sociocultural, cognitive and behavioural contexts central to decision-making, which now require the combination of scientific understanding of risks, with knowledge on how these are framed and perceived by society. This has been the case of climate change in general and adaptation decision-making in particular, making formal assessments to move from a technocratic and expert-led exercise to a more participatory process of decision-support (Jones et al. 2014), also referred to as transdisciplinarity (Pohl & Hadorn 2008; Kirchhoff et al. 2013).

Generically, the contexts for adaptation decision-making usually referred to in the literature are of a social (i.e. cultural values, psychology, language and ethics) and institutional nature (i.e. institutions and governance) (Jones et al. 2014). It is important to acknowledge that adaptation-related decisions are neither made in isolation from other factors nor are they immune to changes in context specific situations such as culture, economy, politics, resources, institutions, and geography among others (Adger et al. 2009; O'Brien 2012; Adger et al. 2012; Engle et al. 2014). Risks in the context of natural hazards always involve interactions between natural (physical) and human (behavioural) factors and cannot be properly understood without attention to human agency and societal processes including cultural beliefs and world views (Eiser et al. 2012). Cultural differences allocate values and guide socially mediated changes such as adaptation. Several value dimensions can be considered, and environmental, religious or other values appear important in shaping perceptions of climate change and risk, as well as in the adoption of proper response actions (Jones et al. 2014).

It has been argued that psychological factors also play a significant role in climate adaptation decision-making, namely through perceptions, representations, knowledge acquisition, memory, behaviour, emotions and understanding of risk. Additionally, other factors include language and meaning aspects, such as notions related to framing, communication, learning, knowledge exchange, dialog and discussion. Ethical considerations around climate change may include intergenerational equity and solidarity, distributional issues, the role of uncertainty in fairness or equity, economic and policy decisions, international justice and law, voluntary and involuntary levels of risk, cross-cultural relations, and human relationships with nature, technology and sociocultural determinants (Jones et al. 2014). Institutional context associated with rules and norms may constrain and shape valid adaptation responses. Jones et al. (2014) point out that institutions can be formal (e.g. laws and policies) or informal (e.g. norms and conventions), and that virtually all climate-related decisions will be made or influenced by institutions, because of their implications to the choices made by organisations and individuals.

1.5. Decision-relevant adaptation science

Decision-makers and scientists supporting them bring diverse objectives, interests, knowledge, cultural norms and values to adaptation decision-making processes. With effective decision-support, those involved (or having a stake) in adaptation should be able to improve the way competing views are managed by better understanding how various alternatives affect trade-offs between proposed goals (Jones et al. 2014). For example, Information is decision-relevant and useful if it expands alternatives, yields deeper understanding, clarifies choices, and enables the achievement of desired outcomes by decision-makers (McNie 2007; Jones et al. 2014).

Adaptation decision-support can be broadly described as the set of processes that create the necessary conditions for the production of decision-relevant information and its appropriate use. It is expected that such a support is more effective when it incorporates context specificities and takes into account the diversity of types of decisions, decision-making processes and societal dynamics (McNie 2007; Jones et al. 2014).

This should lead to the making of informed choices supported by information that is regarded as salient, credible and legitimate (McNie 2007; Jones et al. 2014). Legitimate information should be perceived as free from political bias or stakes, credible information should be perceived as accurate, valid and of quality, and salient (or relevant) information should be context-sensitive by properly considering necessary ecological, temporal, spatial and governance scales. However, consideration of such criteria should be balanced, not focusing excessively in one of the criterions while undermining the quality of the others (McNie 2007).

The above criteria have led to some common principles of effective and useful adaptation decision-making support that, in turn, have prompted different decision-support approaches depending on the contexts of the decisions in question. Some examples of these principles include heuristics like starting with user's needs rather than with scientific interests, emphasize process over products, link users and knowledge producers through tailored systems, increase connectivity across disciplines and organisations, promote institutional stability, and incorporate learning (Jones et al. 2014). Some studies reveal that such principles have been responsible for the growing importance given to the co-production (i.e. together with stakeholders and decision-makers) of knowledge and tools to deal with uncertainty (Hanger et al. 2013).

Moss et al. (2013) outlined an agenda for problem- (or practice-) oriented adaptation research that aims at increasing the support-focus of adaptation science, considering a broad range of necessary societal adjustments. The authors describe four areas that require further improvements to enhance the adaptation research relevance for adaptation practice, namely a better understanding of decision processes and knowledge requirements, identification of vulnerabilities, improving foresight about climate risks and other stressors, and better understanding of barriers and options for adaptation. Moss et al. (2013) further argue for the need of a clarification of the types of scientific information required to improve decision-making, aiming at reducing the so called 'usability gap' in climate-related knowledge. Sustained interactions between researchers and decision-makers are expected to contribute to a better understanding of how climate information can be used in decisions. The development of models and tools that provide tailored assessments of uncertainties and decision-analytical approaches are seen as necessary to facilitate decision-making.

For some time now, decision-support and stakeholder involvement have taken up a central role in climate-related decision-making, particularly for adaptation decision-making. These have covered methods that reflect concrete experiences in climate adaptation assessments (Jones et al. 2014). For example, decision-support for climate services (and adaptation services) has sought to develop different processes of interaction and forms of communication. These have focused on the provision of useful data sets and models, training, data ports and websites, and increased engagement at multiple levels of governance (NRC 2001; WMO 2009; Hewitt et al. 2012; Goosen et al. 2013; Jones et al. 2014).

Evidence gathered through decision sciences demonstrates that "good" scientific and technical information alone may be insufficient to assure "better" decisions (Pidgeon & Fischhoff 2011; Kirchhoff et al. 2013). Eiser et al. (2012) argue that risk-related decision-making under uncertainty is no longer adequately described by traditional 'rational choice' models and that attention needs to be paid to the way personal interpretations of risk are shaped by beliefs, values and societal dynamics. McNie (2007) highlights that concentrated efforts in increasing the supply of scientific information may well not be producing the sorts of information decision-makers see as relevant and useful. Pidgeon & Fischhoff (2011) argue that in order to realize the potential of climate-related research, decision-makers need to understand the risks and uncertainties that are relevant for the decision they face. However, promoting that understanding may well not be a sufficient condition for effective adaptation (and mitigation) responses to the risks posed by climate change, since large political and physiological barriers will also need to be tackled. The surveyed literature supports the view that the production of useful scientific information for adaptation decision-support is not just about the product but also about the process, and that that one of the most important knowledge gaps is the current understanding of how practical adaptation decisions function in real-life settings and contexts. Scientific research also incorporates particular worldviews and implicit assumptions in the way it frames concepts and theories. Often, what distinguishes expert from less expert interpretations of risk is the understanding of the relevant causal processes, and its incorporation into formal models that allow for simulation and experimental testing, rather than the access to data and information (Eiser et al. 2012).

There is strong evidence that, like in other complex domains, effective adaptation decision-making may need well-developed science-policy interfaces (van der Sluijs 2005; van den Hove 2007; van der Sluijs et al. 2008; Swart et al. 2009; Huitema et al. 2011; Hanger et al. 2013; Kirchhoff et al. 2013; Spruijt et al. 2014). Nonetheless, adaptation seems to be the most important topic political scientist are not studying (Javeline 2014), thus leaving out a fundamental disciplinary perspective on the issue.

Dessai et al. (2004) roughly grouped the frameworks used to inform climate adaptation policy in two major paradigms, namely a ‘top-down’ and a ‘bottom-up’ attitude. Dessai & van der Sluijs (2007) pointed that the difference between the two is the direction of the causal chain that is followed in the reasoning behind the application of a given method or analysis. These two paradigms have been widely used to frame impact and adaptation assessments (Dessai & Hulme 2004) decision frameworks and analysis tools (Dessai & van der Sluijs 2007), risk assessment methods, disaster risk management, the appraisal of economic losses (IPCC 2012), and the treatment of uncertainties in support of practical adaptation decisions (Capela Lourenço et al. 2014, Jones et al. 2014).

The management of uncertainties related to climate decision-making is often framed as either a “predict-then-act” or an “assess-risk-of-policy” approach or framework (Lempert et al. 2004; Jones et al. 2014). The literature referring to such approaches is extensive and often uses nuanced terms for both approaches. Therefore, the former paradigm is also known as “top-down”, “model-” or “impacts-first”, “science-first” or “standard” approach, while the latter is also called “bottom-up”, “context-first”, “decision-scaling”, “vulnerability”, “tipping point”, “critical threshold” or “policy-first” approach (Jones et al. 2014). Other definitions for these two opposing, but often complementary approaches, include the terms “predictive top-down” or “optimization” versus “resilience bottom-up” or “decision-first” (Dessai & van der Sluijs 2007; Capela Lourenço et al. 2014).

While it is beyond the scope of this introduction to go into finer detail about these two approaches (or ‘schools of thought’) it is still important to recognize their influence in the way uncertainties are managed in support of decision-making, including the methods and tools that are applied and the engagement level of decision-makers. For reviews and relevant discussions on available strategies to account for uncertainty in decision-making, see Dessai & van der Sluijs 2007 and Capela Lourenço et al. 2014). These include top-down approaches (e.g. prevention principle, IPCC approach, and risk approaches), bottom-up approaches (e.g. precautionary principle, engineering safety margins, anticipating design, resilience, and adaptive management), and mixed approaches (e.g. human development approaches, adaptation policy framework, and robust decision-making).

CCSP (2009) points out that because of theoretical and practical reasons there are limits to the applicability and utility of classic decision-making in the analysis to climate-related problems. The authors further stress that there are two strategies that may be especially attractive when faced with deep uncertainty namely, resilient strategies (assess the range of future circumstances and seek to identify approaches that work reasonably well across that range), and adaptive strategies (choose strategies that can be modified to achieve better performance as one learns more). These strategies stand in sharp contrast with the idea of developing optimal strategies.

Regarding decision-making frameworks and uncertainty analysis tools, Dessai & van der Sluijs (2007) describe the top-down approach as one that explores the accumulation of uncertainties down the 'cascade of uncertainties' (see previous section) before reaching a range of possible local impacts that provide quantification to adaptation needs. Under this perspective, uncertainties about climate change need to be characterised, reduced, managed and communicated. On the other hand, the bottom-up approach is described as starting with an analysis of how robust or resilient a system is to climate variability and change (decision-making context) and then exploring what adaptations are required to make that system less prone to uncertain changes (Dessai & van der Sluijs 2007; Jones et al. 2014). This approach accepts that some uncertainties associated with climate change are irreducible, and thus places a larger emphasis in learning from past events.

With respect to the engagement of decision-makers and stakeholders, it is usually pointed out that a "top-down' framing describes the climate or impact uncertainty independently of other parts of the decision problem, while a "bottom-up" approach often requires information providers to work more closely with decision-makers. The latter is said to be necessary in order to understand their plans and goals, before customising the uncertainty description that fits to those key factors (Jones et al. 2014).

Multiple uncertainty analysis and management methods and tools have been developed and applied to adaptation decision-making, over recent years. Dessai & van der Sluijs (2007) provide an extensive review of tools of relevance for the support of climate adaptation decision-making making. These notably include, scenario analysis ("surprise-free"), expert elicitation, sensitivity analysis, Monte Carlo simulations, probabilistic multi model ensembles, Bayesian methods, NUSAP/Pedigree analysis, fuzzy sets/imprecise probabilities, stakeholder involvement, Quality Assurance/Quality Checklists, extended peer review (i.e. review by stakeholders), and wild cards/surprise scenarios.

Science-supported decision-making has been the focus of research in multiple scientific and societal fields (Willows & Connell 2003; Ranger et al. 2010; Adger et al. 2012). Many environmental, economic and societal decision-making processes as well as their underlying knowledge base, tend to be framed from a particular disciplinary perspective (e.g. natural sciences vs. social sciences; basic vs. applied science; technological or economic vs. environmental focus). Climate adaptation decision-making processes are not a novelty in this regard. Experience has shown that implementing and communicating climate change impacts and vulnerability assessments in support of practical decision-making is a significant challenge (Adger et al. 2005; Tompkins et al. 2010). It has been argued that no single method suits all adaptation-related decision-making contexts, and that, operationally, there is no single definition of risk applicable to all situations (Jones et al. 2014).

With an increasing complexity of management because of climate change, development and other pressures, some reflexive decision-making processes have emerged under the general topics of adaptive management, iterative risk management and community-based adaptation (Jones et al. 2014). However, few assessments of adaptation delivery and effectiveness are available (McNie 2007).

1.6. Adaptation decision-making under uncertainty

The public profile of climate adaptation research and policy-making has grown since at least the late nineteens (Dessai & Hulme 2004). Research into climate adaptation (and adaptation-related) decision-making has been gaining considerable amount of attention, in both developed and developing countries, and for a significant number of sectors (Fankhauser et al. 1999; Klein & Maciver 1999; Kates et al. 2001; Adger et al. 2003; Adger et al. 2005; Smit & Wandel 2006; Ford et al. 2011; Jones et al. 2014). However, research into what exactly are adaptation decisions and how these have handled uncertainties is much scarcer.

Hansson (2005) points out that almost everything that a human being does involves decisions and that, to theorize about decisions is practically equal to theorize about human activities. A major aim of climate-related (e.g. adaptation) decision-making is to make good or better decisions, but no universal criterion for what 'good' or 'better' decision exists. Evidence has pointed out that 'good' science or technological information alone is rarely sufficient to make up for 'better' decisions and that, relatively to other environmental and societal contexts, adaptation-related decision-making has the additional difficulty of having to deal with very long time-scales, pervasive impacts and risks, and associated 'deep' uncertainties (Jones et al. 2014).

In general, if positioned in a broader adaptation-related context, or as they naturally occur in a risk management cycle, adaptation decision-making processes are usually described as multi-stage, interactive cycles. Although context-specificities have to be acknowledged, the adaptation decision-making cycle is generally conceptualised as encompassing an initial stage of framing of the adaptation problem, followed by (a set of) decision-support activities (e.g. research, consulting, policy analysis), the making of the actual decision, and finally the monitoring and evaluation of its outcomes.

The literature shows that the conceptual descriptions of adaptation (and adaptation-related) decision-making processes (or cycles) do share some common features, namely, their interactive nature, the presence of multiple steps (or stages), feedback mechanisms, and a growing representation of complexity, including both in the number of involved agents as in the links across them (i.e. decision-makers and decision-support agents). However, Willows & Connell (2003) argue that the entry point to these processes is not necessarily always the same and that, in practice, the stages in decision-making do not always follow from one another in a consecutive manner. It is often necessary to return to previous steps, as for example, to take into account new options identified only after a first round of assessments or appraisal work.

Because decision-making processes often comprise a high level of uniqueness and solutions are frequently determined on a case-by-case basis, it has been pointed out that, each decision goes through its own (and sometimes unique) process of development and implementation. In turn, this means that the involvement of researchers or other analysts may take many potential different formats (Walker et al. 2003). Different systems may also need to be assessed differently and pre-existing conditions may influence the way a decision-maker acts and goes through this cycle (Walker et al. 2003). These issues raise the question of whether, for example, it is possible to extract comparable and valuable lessons from how other decision-makers, in different cultural and socio-economic contexts, are supported by research, deal with uncertainty, and ultimately how they decide about adaptation actions.

Several frameworks (in turn, including a wide variety of methods and tools) have been developed to support decision-makers addressing uncertainties in the development of their policies and plans. For examples and relevant discussions on the issue, see Walker et al. (2003), Willows & Connell (2003), Dessai & Hulme (2007), CCSP (2009), Dessai & Wilby (2010), Ranger et al. (2010), Reeder & Ranger (2011), Hanger et al. (2013), Patt (2011), and Swart & Singh (2013).

McNie (2007) describes every environmental decision-making process as having seven phases namely, gathering intelligence, promoting alternatives, prescribing, implementing and applying the solution, terminating the decision, and evaluating the decision. Decision-making has been widely studied in many fields and some research has rejected the notion that decision-making processes are rational by definition, context independent and of sequential nature, thus pre-empting the use of theories for predictive purposes on the matter. However, such theories and frameworks can be useful for decision-making through simplification and suggestion of what is important to consider and what can be discarded during the process.

Walker et al. (2003) defines an idealized multi-stage iterative process consisting of, namely, problem identification and framing, decision-support activities (e.g. policy analysis), quality control (e.g. peer-review of the analysis performed), evaluation of analysis outcomes (e.g. by policy-makers and stakeholders), and finally the stages of policy decision, implementation, communication (e.g. to the public) and monitoring. It is further noted that decision-support activities must often explore the effects of alternative policies on the full range of outcomes and under a variety of scenarios, as well as examine trade-offs among diverse policies. This exploration often requires a structured analytical process and some modelling of the system of interest - either the system as it exists, or as it is envisioned in a different (e.g. future) context (Walker et al. 2003).

Willows & Connell (2003) propose a structured risk-uncertainty framework and guidance for good adaptation decision-making. Their decision-making support framework aims at helping decision-makers identify risk factors as associated uncertainties, and consists of a set of (tiered) eight-stages: identify problems and objectives; establish decision-making criteria; assess risk; identify options; appraise decision; make decision; implement decision; and monitor, evaluate and review.

This framework has been widely adapted and used in analysis, guidance and development of adaptation strategies and plans, particularly in the UK and Anglophone countries (Ranger et al. 2010; Goosen et al. 2013; Bours et al. 2013). The UKCIP Adaptation Wizard (UKCIP 2013), a widely used and replicated online tool to help decision-makers to adapt to climate change, is based in the Willows & Connell (2003) framework. Because of its application to adaptation strategies, plans and other decision-support activities, both public and private, across a variety of sectors, countries and regions, the use of the original risk-management framework has now been expanded across the world. Ranger et al. (2010) further develop the Willows & Connell (2003) work, by detailing a comprehensive guidance for decision-making under uncertainty, and applying it to the UK adaptation context using four case studies about the food sector, water sector, flooding and ecosystems and biodiversity.

The above frameworks aim at capturing and describing the complexity of (science-supported) adaptation-related decision-making processes. They also represent a strong case for decision-centred approaches by providing pragmatic guidance on scoping complex, identifying pertinent information, interpreting projections and selecting methods that are appropriate to the nature and level of uncertainty faced by adaptation decision-making. Included in these efforts is also the development of a variety of methods and tools for dealing with uncertainty, long time horizons, diverse knowledge types and contested values between the involved actors in distributed decision-making (Wise et al. 2014).

Research into decision-oriented approaches has become evident in recent years, as these seem to be regarded as being “better” able to tackle the challenges of planning for future uncertain consequences of change, unpredictable values and preferences of future societies (Wise et al. 2014). Over the past years, adaptation has been framed in multiples ways and adaptation research (and to some extent also adaptation practice) has seen multiple analytical developments (e.g. methods, tools and frameworks) that ranged from completely positivistic/reductionist perspectives, to more rationalist and even post-normal science approaches (Dessai & van der Sluijs 2007; Kirchhoff et al. 2013; Wise et al. 2014). The latter are seen as being potentially suitable for situations in which the stakes are high, values are disputed, decisions are urgent and the science is uncertain (Funtowicz & Ravetz 1990; Funtowicz & Ravetz 1993; Funtowicz & Ravetz 2003; van der Sluijs et al. 2003; van der Sluijs et al. 2005; Kirchhoff et al. 2013). For some examples and discussion of its application to climate adaptation and other environmental decision-making process, see van der Sluijs et al. (2003), Janssen et al. (2004), van der Sluijs et al. (2005), van der Sluijs et al. (2008), Wardekker et al. (2008), Lorenz et al. (2013). Most of currently available examples refer to the work carried out in the Netherlands, although recent work by Lorenz et al. (2013) expanded it to a European-wide context.

Despite the rapid evolution and growing complexity in the models that mediate science-society interaction, it has been argued that the use of scientific knowledge in climate change related decision-making remains below expectations, suggesting that a significant gap between adaptation knowledge production and use persists (Kirchhoff et al. 2013). While techniques for addressing uncertainties in future climate change have evolved (e.g. development of Bayesian probabilistic climate projections), these scientific advances do not always translate into improved decisions or clearer treatment of uncertainty in practice (Mearns 2010), sometimes even having the opposite effect (Hall 2007; Tang & Dessai 2012). Although adaptation plans are growing at multiple scales, they seem to be yet under-developed. These plans reflect a preference for capacity building over delivery of specific vulnerability-reduction measures, indicating that current adaptation planning is still informal and ad-hoc (Jones et al. 2014).

Climate change creates an additional layer of uncertainty for decision-makers, who already face multiple short-term and strategic economic, social and political (i.e. non-climate) challenges. Despite improvements in the climate change science-policy interface (Rayner & Jordan 2010), most decision-makers do not routinely consider future scenarios when making decisions, nor do they find it easy to make use of available knowledge on climate change and impacts (Kandlikar et al. 2005; Hulme et al. 2007; Porter et al. 2012; Porter et al. 2014). A common problem is the mismatch between the spatial and temporal scales of what is known about the world and the scales at which decisions are made and actions are taken (Kates et al. 2001).

However, Dovers (2009) argues that societies have already developed capacities and understanding in multiple policy sectors that can provide a basis for addressing both observed (existing) and (future) significantly exacerbated variability, insofar it remains within the limits of human experience. In many cases, well-developed and already available policy and management proposals have been developed for reasons other than future climate change and variability and are not isolated from other decision-making contexts. Adaptation responses that build upon existing policy agendas and are mutually supportive of both climate adaptation and other societal goals, may accelerate the implementation of better climate adaptation practices.

Climate adaptation decision-making has been so far largely modelled on the scientific understanding of cause-and-effect, which postulates that increasing greenhouse gas emissions and their raising atmospheric concentrations will cause climate to change, thus resulting in impacts and changing risks, and in potential increased vulnerability to those risks. The resulting decision-making guidance on adaptation has followed a traditional rational-linear process in identifying potential risks and appraising management responses. This sort of processes have been challenged for not properly addressing the diverse contexts within which climate change decisions are made, often neglecting previously existing decision-making processes, and overlooking various cultural and behavioural aspects of decision-making (Jones et al. 2014).

While the literature about adaptation options is fertile in pointing out 'what to do' and providing examples of on-going adaptation actions, it generally lacks substantive explanations of 'how to do it', for example, in relation to the implementation of decision-support methods and approaches. This becomes clear by looking at the literature surveyed in the IPCC reports (see IPCC 2013, IPCC 2014a, IPCC 2014b). Using a wide variety of case-studies, the IPCC (2014b) points out that regional and local adaptation will incur increasing costs for upgrading coastal defences, energy production, energy use, agriculture, and adapting buildings (houses, schools, hospitals), but does not mention if methods for decision-making in all these sectors are readily available to support such measures. It rather focuses on detailing the constraints and enabling factors, pointing to widely used techniques that are expected to help reducing the challenges for decision-making (e.g. precautionary principle, real options, adaptive management, no regrets strategies, risk hedging and adaptation pathways).

Recent literature on adaptation decision-making under uncertainty (Hallegatte 2009; Stafford Smith et al. 2011; Wise et al. 2014) highlights two key gaps on these areas. Firstly, the emerging need for innovative strategies in the development of uncertainty-management methods. Secondly, the notion that such methods need to be framed within a broader sorting of decision types that are adequately systematised into adaptation support frameworks. Hallegatte (2009) emphasises that decision-makers need to adjust their current practices and decision-making frameworks by, for example, adapting their uncertainty-management approaches.

The long-time commitment of adaptation decision-making in a wide range of sectors and (human or natural) systems necessarily makes decisions very climate sensitive. Examples include urban planning, water management or transport infrastructures and building design and regulations.

These decisions and investments can have long lifetimes of up to 100-200 years and thus may have to cope with very different climates by the end of the century and beyond. If climate (and other) changes are to be properly incorporated into the decision design and implementation, those involved in the decision-making processes need to be aware and account for future changes, leaving behind the notion of stationarity (Hallegatte 2009).

Long-term commitments for planning and investment as well as some degree of irreversibility in the available choices makes it necessary, for several areas of society, to already have to consider climate change. Decision-makers such as architects, water managers, urban and other sector engineers and planners face increasing uncertainty in their activities because of climate change. Hallegatte (2009) points out that this challenge may require new decision-making approaches, as current decision-support methods become increasingly hard to apply. By using examples from the building and water management sectors, the author describes two major issues that are faced when considering climate change data.

The first is a scale issue between what is provided by climate, impact and vulnerability models and what is required by the decision-maker. Downscaling techniques and other approaches have been developed and applied in many contexts, to help evaluate and manage this and other problems associated with scale and use of modelling outputs. Multiple examples of applications and guidance are widely available in the literature (see Wilbanks & Kates 1999, Trigo & Palutikof 2001, Benestad et al. 2007, IPCC-TGICA 2007, Fowler et al. 2007, van Vuuren et al. 2007, Giorgi & Lionello 2008, IPCC 2013, IPCC 2014b, Pulquério et al. 2015).

The second problem is harder to address and deals with the potential similarity between model outputs and observed data, commonly used to make technical decisions (Hallegatte 2009). Because of the level of uncertainty associated with climate change (i.e. usually scenario uncertainty, see section 1.4), decisions-makers face the challenge of taking such outputs for their face value. Traditionally used decisions-support tools (e.g. engineering formulations of all sorts) have been developed to function under stationary climate data (e.g. one figure for one formula, representing statistical uncertainty levels) and are not equipped to work under multiple and often contradictory inputs. Hallegatte (2009) depicts two examples of this situation. The first uses a hypothetical French water resource manager having to deal with information that ranges from unchanged precipitation levels to a decrease of 30% while retrofitting water infrastructures. In the second one, a French architect would have to plan now, a Paris building that over 80 years' time would see its climate envelope warm up to the levels of current Cordoba (Spain) climate.

Hallegatte (2009) asserts that since climate information provided by models and observations is not able to provide what current decision-making frameworks need, then these frameworks need to be amended to consider uncertainty. This means, for example, that infrastructure design needs to acknowledge a larger range of climate conditions and that this range will remain uncertain. In order to favour robustness and further consider uncertainty-management in the decision-making framework, the author proposes a suit of different methods. These include, using no-regret strategies (e.g. that will yield benefits even in the absence of climate change), favouring reversible and flexible choices (e.g. that lower the costs of making a mistake), applying safety design margins (e.g. over-dimensioning to account for uncertain changes). Additionally other methods are proposes such as, favouring soft strategies (e.g. institutional changes), reducing decision-making time horizons (e.g. avoid long-term commitments in favour of shorter-lived decisions) and accounting for conflicts and synergies with other strategies (e.g. mitigation).

Weaver et al. (2013) reviewed the need for, use of, and demands on climate modelling to support so-called ‘robust’ decision frameworks, in the context of improving the contribution of climate information to effective decision making. The authors argue that there is a severe underutilization of climate models as tools for supporting decision-making. They further pointed that this may actually be slowing the progress in developing informed adaptation action, and suggested that addressing the causes would require expanding the conception of climate models. However, such a shift would have likely implications in the way users perceive and use information generated by models and, ultimately, in the types of information that are demanded from these models.

Stafford Smith et al. (2011) recognises that it is challenging to include climate change in decision-making frameworks, but argues that there are existing tools that can be used for this. He further suggests that the five approaches proposed by Hallegatte (2009) need to be framed within broader classification of decisions, setting out an initial classification of decision types aimed at supporting decision-makers to reach better adaptation responses (see table 2). Building on the work by Hallegatte (2009) and Adger & Barnett (2009), the authors outline a systematic approach that categorises the interactions between decision lifetimes, types of uncertainty driver and the nature of the adaptation responses. One of the proposed objectives of this initial categorization is to advance the understanding of adaptation decisions with long lifetimes, by contrasting them with simpler and shorter-term adaptation decisions.

Regarding decisions lifetime, Stafford Smith et al. (2011) argue that four types of interactions can be described, namely short lead and consequence time (e.g. choosing between cultivars), short lead time and long consequences (e.g. building individual houses), long lead time and short consequences (e.g. developing new cultivars) and finally, long lead and consequence lifetimes (e.g. urban planning). In practice, climate change will potentially play a major role in decisions with long total lifetimes while decisions with shorter total lifetimes can wait until climate change is experienced before considering it. Longer lifetimes may imply diverging and potentially different climate futures, thus requiring the consideration of increasingly transformational adaptation. The authors argue that the multiple combinations between these factors determine the treatment required for different adaptation decisions, mapping out how these reflect in the characteristics of decision-making frameworks and on the application of the Hallegatte (2009) proposed approaches.

Table 2 - Implications of different combinations of decision lifetimes, driver uncertainty type and adaptation response types for decision-making strategies and tactics under diverging climate futures [Source: Stafford Smith et al. 2011].

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

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

Stafford Smith et al. (2011) details three different forms of adaptation responses in a decision, which they characterize regarding the type (e.g. different options) and extent (e.g. the size or design of an option). Adaptation options that can be of the same type and extent regardless of the driver of uncertainty are usually referred to as no-regret options since they will be able to yields positive outcomes regardless if they change is monotonic or indeterminate. Adaptation responses of the same type but with different extents according to the climate signal are choices that consider the application of the same option but with different designs (e.g. choosing between different size and height of a coastal defence infrastructure, according to different projected sea-level heights). Responses that require consideration of different types and extents (e.g. sea wall versus sand replenishing) are in fact decisions that have to choose not only between different options, but also between different designs of those options.

The implications of different combinations of these three factors can be mapped against different adaptation decision-making approaches. Stafford Smith et al. (2011) highlight some of the available methodologies to lower the risk of making each type of decision (see table 2 for a summary). However, the authors stress that this classification is born out of the experience in Australia and the UK, and that the context of adaptation decisions in developing counties may differ.

Climate-related decisions have similarities and differences with decisions concerning other long-term, high-consequence issues. Commonalities include the usefulness of using broad risk-management approaches and the need to consider uncertain projections of various biophysical and socioeconomic conditions. However, adaptation decision-making frameworks have to include longer time horizons because they can potentially affect a broader range of human and Earth systems, compared to many other sources of environmental and societal risks.

1.7. Thesis rationale, aims and structure

As stated before this thesis is about advancing the understanding of climate adaptation-related decisions and decision-making processes, and of how science supports and equips them to handle uncertainty. The current state of the art reviewed in this introduction demonstrates that in order to further develop the way 'good' or 'better' adaptation decisions are made, it may be necessary to:

- Enhance the current understanding of how adaptation decisions are made and how decision-making processes occur in reality;
- Properly describe and account for how the need to handle uncertainty in these processes is supported by science and other practices;
- Frame uncertainty-management methods within a broader sorting of adaptation-related decision types, systematize them according to decision's needs and factor them in to general support frameworks.

This thesis is subdivided into several complementary issues so it is important to provide a general overview of its structure and chapters. A lot of the current interest in the climate adaptation topic, both in the research and policy arenas, has to deal with how to move from theory to practice. This means that adaptation (or adaptation-related) decisions need to become visible in multiple sectors and domains of society (e.g. policy-making, social systems, infrastructures, fiscalism, and law, among others). Therefore, choices have to be made. A common trait of this sort of decisions is that they will always have to deal with deeply rooted uncertainties, and that they are about valued objectives, structures and/or processes. In most cases, these decisions will have to factor in conflicting views and values across individuals and organisations. This particular set of characteristics turns such choices into so-called 'wicked problems'. It has been proposed that this type of problem will be more efficiently handled if the science that underpins it is participatory and transdisciplinary in nature. This means using the decision-makers' (or stakeholders) own knowledge, perceptions and values to co-create and co-develop research. Ultimately, it also means to mediate between the more disciplinary (and theoretical) scientific knowledge about adapting human and natural systems and the more practice-oriented information expected to make up for 'good' or 'better' adaptation decisions. About a decade ago, planned adaptation entered the climate change discourse as a concrete need rather than a conceptual framing of action. Since then, significant evolution in both adaptation research and policy has been recorded. Yet, it has been recently suggested that current adaptation planning is still under-developed, of an ad-hoc nature at best, and much more centred in capacity building than in the delivering practical vulnerability-reducing actions. This most likely means that the *science for adaptation* - practice oriented and transdisciplinary research supporting adaptation efforts - has been highly active in recent years. But it may also well mean that its purportedly underlying basis, the *science of adaptation* - a disciplinary and plural research inquiry field that tries to better understand the multiple facets of adaptation as a response to climate change - is still very much lagging, and thus in need of development (Chapter 2). It should be noted that a great deal of the author's own work could be included in the former type of research. Uncertainty management in adaptation decision-making is just one of the multiple examples of this broader trend and one where the issue of transdisciplinarity vs. disciplinary and plural research inquiry can be markedly observed. This thesis seeks to advance the understanding of why and how adaptation decisions occur (or not) in practice and how they handle uncertainty (Chapter 3). Finally, this thesis lays the ground for a general framework that locates some of the challenges related to the need of further developing a sound (environmental but also applied) science basis for 'good' or 'better' climate adaptation decisions to be made under uncertainty (Chapter 4).

This PhD thesis includes one journal paper, two book chapters (published in a book fully edited by the author) and one proceedings article, all of which were peer-reviewed. Several other research results by the author have informed this thesis. Some have been published as editorials and other were not published as scientific stand-alone papers, so where not included here. A full list of publications and projects by the author can be found in the Curriculum Vitae annexed to this thesis.

The publications composing this thesis are:

Chapter 2 - Decision-relevant adaptation science

1) Swart, R., Biesbroek, R. and **Capela Lourenço, T.** (2014) *Science of adaptation to climate change and science for adaptation*. Front. Environ. Sci. 2(29):1-8, DOI: 10.3389/fenvs.2014.00029.

Chapter 3 - Uncertainty and adaptation decision-making

2) **Capela Lourenço, T.**, Rovisco, A., Groot, A., van Bree, L., Street, R., Garrett, P. and Santos, F.D. (2013) *Making adaptation decisions: the far end of the uncertainty cascade*. Impacts World 2013, International Conference on Climate Change Effects, Potsdam, 27-30 May 2013.

3) Groot, A., Rovisco, A., and **Capela Lourenço, T.** (2014) *Showcasing practitioners' experiences*, in **Capela Lourenço, T**., Rovisco, A., Groot, A., Nilsson, C., Füssel, H-M, van Bree, L. and Street, R. (Editors) (2014) *Adapting to an Uncertain Climate: Lessons from Practice*. Springer, the Netherlands, 182pp, ISBN: 978-3-319-04875-8.

Chapter 4 - New adaptation decision-making frameworks

4) **Capela Lourenço, T**., Rovisco, A., and Groot, A. (2014) *Making adaptation decisions under uncertainty: lessons from theory and practice*, in **Capela Lourenço, T**., Rovisco, A., Groot, A., Nilsson, C., Füssel, H-M, van Bree, L. and Street, R. (Editors) (2014) *Adapting to an Uncertain Climate: Lessons from Practice*. Springer, the Netherlands, 182pp, ISBN: 978-3-319-04875-8.

Chapter 1 describes some of the key underlying concepts and terms that are useful for this thesis. It also reviews previous efforts at defining and characterizing adaptation decisions and decision-support activities, as well as earlier attempts to develop generic frameworks to handle uncertainty in adaptation decision-making processes. **Chapter 2** provides a nuanced discussion (publication No. 1) on the merits, pitfalls and challenges faced by adaptation science and research programming, outlining a diversification approach as a potential way forward in this area. Current examples of uncertainty-management in real-life adaptation decision-making situations are described and analysed in **chapter 3** (publications No. 2 and 3). **Chapter 4** distils much of the information gathered in the previous chapters and proposes a way forward by systematising a generic framework for characterizing and supporting adaptation decisions under uncertainty (publication No. 4). Finally, **chapter 5** presents key reflections and discusses the implications, conclusions and limitations of this thesis, finalising with some ideas for further work.

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CHAPTER 2: DECISION-RELEVANT ADAPTATION SCIENCE

Publication I - Science of adaptation to climate change and science for adaptation

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This paper is published in the *Frontiers of Environmental Science & Engineering* journal and should be referenced as: Swart, R., Biesbroek, R. and Capela Lourenço, T. (2014) Science of adaptation to climate change and science for adaptation. Front. Environ. Sci. 2(29):1-8, DOI: 10.3389/fenvs.2014.00029.

frontiers in ENVIRONMENTAL SCIENCE

REVIEW ARTICLE
published: 02 July 2014
doi: 10.3389/fenvs.2014.00029

Science *of* adaptation to climate change and science *for* adaptation

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Adaptation to climate change has gained a prominent place next to mitigation on global, national, and local policy agendas. However, while an abundance of adaptation strategies, plans, and programmes have been developed, progress in turning these into action has been slow. The development of a sound knowledge basis to support adaptation globally is suggested to accelerate progress, but has lagged behind. The emphasis in both current and newly proposed programmes is very much on practice-oriented research with strong stakeholder participation. This paper supports such practice-oriented research, but argues that this is insufficient to support adaptation policy and practice in a productive manner. We argue that there is not only a need for science *for* adaptation, but also a science *of* adaptation. The paper argues that participatory, practice-oriented research is indeed essential, but has to be complemented by and connected to more fundamental inquiry and concept development, which takes into account knowledge that has been developed in disciplinary sciences and on issues other than climate change adaptation. At the same time, the level and method of participation in science for adaptation should be determined on the basis of the specific project context and goals. More emphasis on science of adaptation can lead to improved understanding of the conditions for successful science for adaptation.

Keywords: climate change adaptation, science of adaptation, science for adaptation, transdisciplinarity, adaptation research

INTRODUCTION

Ever since the perceived taboo on adaptation to climate change has been lifted (Pielke et al., 2007), adaptation has become politically accepted and institutionalized at different levels of governance: for example, through the establishment of financial instruments at the global level of the United National Framework Convention on Climate Change (UNFCCC), the European Union's Climate Change Adaptation Strategy, the increasing number of National Climate Change Adaptation Strategies and plans, and the numerous local and regional initiatives to plan for future climate change risks (Biesbroek et al., 2010; Dreyfus and Patt, 2012). Many examples of adaptation have been reported and now serve as an inspiration for future adaptation efforts across the globe. Still, the World Economic Forum considers the failure to adapt to climate change to be one of the major threats that society faces in the coming decades (WEF, 2013, 2014), requiring even more adaptation action.

In parallel to the policy progress, scientific endeavors on understanding different dimensions of adaptation to climate change and the number of scholarly papers has increased substantially in recent years (Berrang-Ford et al., 2011). The recently published 5th Assessment report of IPCC Working Group II is the most recent assessment of the scientific progress on adaptation. Where previous research has explored the impacts and vulnerabilities of climate risks, recent emphasis in adaptation research programmes, globally, and in Europe, has been on responses, in particular on the softer kind of measures such as capacity building, management, and planning, awareness raising and supply of information, but less on actually changing practices, green or gray infrastructure, or measurable decrease of vulnerability (EEA, 2013; Biagini et al., 2014). Moss et al. (2013) argue that inadequate knowledge for adaptation forms one important reason why progress in delivering adaptation action has been limited. Research to support adaptation therefore needs to move toward other forms of research that better connects to the societal needs (Moser, 2010; O'Brien, 2012; Deppisch and Hasibovic, 2013). Conventional disciplinary approaches are considered to be insufficiently equipped to deal with the intricately connected and inherently wicked nature of climate change risks in a holistic way (ISSC/UNESCO, 2013). A multidisciplinary or interdisciplinary approach, where disciplinary knowledge is, respectively, exchanged or integrated, is deemed necessary but not sufficient to tackle these societally relevant problems either.

The inability to connect the sciences meaningfully with societal needs has been central to different academic disciplines and philosophy of science (Nowotny et al., 2001) and recently entered the discussion on climate change adaptation (see amongst others Moser and Boykoff, 2013) and its connections with climate risk management approaches (IPCC, 2012), namely those that aim at combining adaptation and disaster risk reduction processes. It is argued that future research on climate change adaptation would require the involvement of non-scientific stakeholders in the research enterprise so as to co-define societally relevant problems, to co-produce or co-create relevant knowledge, and to co-learn from these experiences, which in this paper, we consider to be captured by the term "transdisciplinary" (Mauser et al., 2013; Rice, 2013). The term "transdisciplinary" is defined differently in different contexts and its meaning has evolved over time. Defining characteristics are usually problem focus, evolving methodology, and collaboration, with a different balance in different contexts (Wickson et al., 2006; Russell et al., 2008). Nowotny et al. (2001) refer to "knowledge production that is problem-oriented, responsive and open to external knowledge producers, contextualized, and systems-based, adaptable, consultative and socially robust." As we observe in the next section, the involvement of external knowledge producers is typical for the definition used in climate change adaptation programming. So, in this paper we explicitly refer to kinds of transdisciplinary research that does create knowledge beyond disciplinary borders and does also involve stakeholders. The ontological questions of what constitutes a transdisciplinary approach, how it originated, and how its success can be evaluated is beyond the scope of this article (Pohl, 2008, 2011). Yet one defining characteristic, namely problem orientation through a participatory approach is central to this paper. It has been argued that transdisciplinary research is particularly relevant when knowledge is uncertain, the nature of the problem disputed and the consequences of the problem affect large parts of society (Hirsch Hadorn et al., 2007). Although the precise onset of this movement in the recent past remains difficult to identify in time, we observe that the scientific discourse on adaptation seems to move in the direction of one unified, practice-oriented, transdisciplinary form of science aiming to inform "decision makers," even though it is often unclear who exactly these decision makers are or which precise questions they have. This movement can be regarded as part of a broader trend which Bäckstrand et al. (2010) labeled the deliberative turn in environmental governance. Although there can be no objection against socially relevant research on adaptation, we feel that there are some critical reflections and nuances currently missing in the debates on the future of adaptation research, which we will discuss in this paper.

First, we review some of the key elements of current and proposed adaptation research programmes related to practice-oriented research and identify their strengths and weaknesses—which we call the science *for* adaptation. Then we focus on the need for—and early efforts on—a science *of* adaptation. Finally, we discuss a number of future directions that this research can take to build both a science *for* and *of* adaptation, and connections between them.

PRACTICE-ORIENTED RESEARCH PROGRAMMES ON CLIMATE CHANGE ADAPTATION

Although the call for transdisciplinary and practice-oriented research on adaptation has been relatively recent, several research programmes aiming to support adaptation that reflect this call have already been developed and, in some countries, implemented (Mauser et al., 2013). Some important programmes are summarized below. We illustrate this trend by highlighting the ambitions of several exemplary transdisciplinary research and funding programs at international, European and national levels. As these research programmes are often still in the implementation or proposal stage, a systematic quantitative analysis of published papers on climate change adaptation projects funded through these programmes is not yet possible.

At the global level, the Future Earth programme is perhaps most relevant for adaptation research. Although the programme targets sustainability issues wider than adaptation, it provides a global umbrella for adaptation-relevant research (Future Earth, 2013). To address the challenge that science has up-to-now tended to provide mainly understanding but not answers or comprehensive solutions to sustainability questions, Future Earth proposes co-design and co-production of research, noting that this kind of research is also sometimes referred to as "transdisciplinary" (Future Earth, 2013).

A major new research initiative in Europe in support of climate change adaptation policy development is the Joint Programming Initiative (JPI) Climate a collaboration between 14 European countries to coordinate jointly their climate research and fund new transnational research initiatives. JPI Climate intends to connect scientific disciplines, enable cross-border research, and increase science-practice interactions (JPI Climate, 2010). One of the four elements of JPI Climate specifically aims at "facilitating transdisciplinary exchange on the objectives, the framework conditions and the realization of sustainable societal transformations toward "carbon neutral," adaptive and climate–proof European societies through interaction and joint initiatives with stakeholders as knowledge partners." Another JPI element focuses on improving models and scenario–based tools for decision–making under climate change, tools which "will be further developed, compared, and applied in close interaction and dialogue between researchers and stakeholders at different levels."

JPI Climate could be regarded as the EU Member State counterpart of the new Horizon2020 (H2020) programme. This latter programme is a new major endeavor of the European Commission with three main objectives: excellent science, industrial leadership, and societal challenges. The total budget is nearly €80 billion, of which more than €15 billion over the first 2 years, 35% of which should be climate related (EC, 2013). Although H2020 is more oriented toward policy support than its Framework Programme predecessors, transdisciplinarity is not explicitly identified as an action point. Nonetheless, the programme extensively calls for user-driven (or -relevant) research and societal engagement, explicitly embedding Social Sciences and Humanities (SSH), which is also meant to stimulate interdisciplinarity and, to a certain extent, transdisciplinarity (integrating also non-disciplinary knowledge). Transdisciplinarity is furthermore fostered via the actions under EU's Responsible Research and Innovation (RRI) activities (Pauli, 2013). Projects combining research and innovation, aiming at developing markets in collaboration with private sector partners, in particular SMEs, are at the core of H2020.

Pertinent examples of targeted climate change adaptation research programmes at the national level are the KLIMZUG programme in Germany (Bardt et al., 2012) and the Knowledge for Climate Programme in The Netherlands (Hegger et al., 2012; Knowledge for Climate, 2012). Both programmes built on predecessors that focused more on assessment of impacts and vulnerability (klimazwei, and Climate changes Spatial Planning, respectively). Other programmes of groups of projects that have a participatory component have been developed in countries like Japan (Tamura et al., 2014), Australia (NCCARF, 2012), the United States (Moss et al., 2014), Finland, and the United Kingdom. Also the Austrian Climate Research Programme encourages interdisciplinary and transdisciplinary project proposals, "to enhance the quality of project applications and international visibility and knowledge transfer to Austria" (ACRP, 2014).

These examples confirm that current and proposed research programmes relevant for adaptation to climate change at all levels tend to focus mainly, or sometimes exclusively, on practice-oriented research in support of adaptation decision-making. They draw from existing fundamental disciplinary knowledge, but pay less attention to more fundamental research leading to appropriate theoretical frameworks and associated methodologies for adaptation to climate change. Below we discuss the pros and cons of this approach.

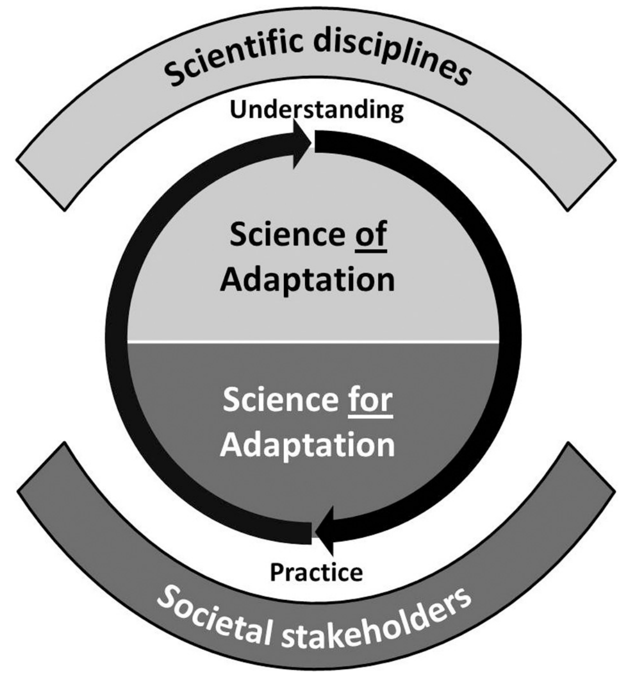

FIGURE 1 | Disentangling "adaptation science" into science *of* and science *for* adaptation. Disciplines include but are not limited to political science, economics, psychology, sociology. Stakeholders can be local, regional, national, or international; public or private.

SCIENCE *FOR* ADAPTATION: PRACTICE-ORIENTED RESEARCH AND BRIDGING THE SCIENCE-POLICY-PRACTICE DIVIDE

The research programmes above demonstrate considerable efforts in practice-oriented research on adaptation. However, one could pose the question if it would be justified to develop a distinct, novel "adaptation science" to support adaptation, or if adaptation is mainly an act of practice, one that can be studied using multiple scientific perspectives. This question is yet to be answered. Some have argued that there are at least some signs of such an emerging "adaptation science." According to Moss et al. (2013), adaptation science is at best still in a formative stage. To address the question what it is and how it may develop, we make the analytical distinction between science *on* adaptation and science *for* adaptation, see **Figure 1**.

Moss et al. (2013) provide a comprehensive proposal for the development of an integrated and practice-relevant adaptation science, to understand decision processes and knowledge requirements, identify vulnerabilities, improve foresight about climate risks and other stressors, and understand barriers and options for adaptation (Moss et al., 2013). Practice-oriented or socially relevant research is unquestionably of utmost importance, and is justified for many societal challenges, including adaptation. However, to what extent does transdisciplinary research indeed lead to societal impacts, e.g., in terms of decreased vulnerability to climate change? More co-produced knowledge is often assumed to lead to more and better adaptation because of tangible connections between the research and social needs and interests (Hegger et al., 2012). But is this really true? An evaluation of the societal impact of the two Dutch climate change research programmes suggests that the impact has been greatest on agenda setting (Merkx et al., 2012). Knowledge on climate change amongst societal actors has been increased, the magnitude, and diversity of networks have been improved, tools have been developed that are also used by actors not involved in the programme, and knowledge has effectively been co-created. However, with a few exceptions, these positive outcomes have generally not led to actual implementation of adaptation actions, and the durability of the impacts is uncertain (Merkx et al., 2012).

We identify several pitfalls of too much emphasis on an imprecisely defined, transdisciplinary, practice-oriented form of research—a science *for* adaptation without a substantive science *of* adaptation. While these pitfalls can be expected to reduce the quality and social impact of this kind of research, this does not imply that addressing these pitfalls will automatically lead to action, since other factors play a role as well, including the limitations of scientific knowledge in general as a driver for societal action (Biesbroek et al., 2013a). We start from the premise that by taking away these barriers the chance of success may be enhanced, and more emphasis on a science *of* adaptation can provide better and more informed interventions in practice. Below we discuss five: (1) application of untested heuristics in practice; (2) scientists as problem-solvers; (3) consensus framing and confusing terminology; (4) unattractiveness for disciplinary researchers, and (5) a one-size-fits-all approach.

(1) Validated and tested theoretical frameworks and hypotheses as well as appropriate and commonly accepted methodologies and data are as yet largely missing. In such a situation,

practice-oriented adaptation research appears to be driven by unproven assumptions about the effectiveness, costs, and benefits of particular adaptation measures, rather than by a comprehensive, sound analysis of the options, and the conditions under which they may be applied. Preston et al. (2013) argue that current adaptation discussions rely on heuristics that are scientifically untested but which nevertheless resurface in most practices. Such heuristic devices shape how we see adaptation and they influence the policy decisions—practices thrive on heuristic reasoning. The use of largely untested heuristic devices, such as "better adaptation outcomes require stakeholder involvement" (Burton and Mustelin, 2013) or "adaptation is novel and there are no experiences to draw from" (Bassett and Fogelman, 2013) may sometimes prove to be barriers rather than providing support in search for optimal solutions. In addition, it remains unclear when exactly this call for adaptation transdisciplinarity emerged, raising the question whether it was "imported" from other science-practice arenas or emerged from an evolving community of adaptation researchers.

(2) A second pitfall is the challenge of unconscious convergence of perspectives between scientists and practitioners which reduces the ability to reflect and innovate. Policy makers are problem solvers by definition; it is their task, their *raison d'etre*, to help solve societal problems such as climate change adaptation by making policies, programmes, and plans, to provide guidance and support society where needed (Biesbroek et al., 2013b). Policy makers have certain problem framings that do not necessarily match those of scientists. Of course, there are different types of scientists in the climate change adaptation debate, but even for honest knowledge brokers and the most skilled boundary workers, there is the risk that the encouraged closeness between science and practice, forces scientists—inadvertently or involuntarily—to adopt the same paradigmatic lens of the policy maker to connect to a policy framing so as to determine what is socially relevant and practically applicable. Adopting the same problem-solving lens by both science and practice runs the danger that they become trapped in the vicious cycle where the problem-solving paradigm is dominating every discussion and decision on real world problems. Indeed, we know that there are different analytical paradigms, rooted in different traditions, from which to study adaptation (O'Brien and Hochachka, 2010; Biesbroek et al., 2013b). Fixation on one paradigm, in this case that of the "problem solver," means that those involved are unable to take a step back, reflect, and use other lenses and theories to provide meaningful advice in search of practice-relevant adaptation actions (Carolan, 2004; Biesbroek, 2014). Such reflexive distance is, however, of vital importance (Voss et al., 2006).

(3) Transdisciplinary research may lead to consensus frames that are depoliticized and lack the necessary substance to allow for concrete adaptation action. Experiences from interdisciplinary research show that there are communicative and conceptual barriers brought on by disparate research backgrounds and streams of thought, and that barriers become even more challenging by involving non-academic stakeholders with different motives, ideas, or goals. One of the resulting consequences is the construction of framings of apparent consensus; in other words, searching for common framings and understandings, for example by inventing new words to which people from different backgrounds can relate (see **Box 1**). Consensus frames are partly the result of the translatability of the disciplinary understandings and the emerging of new scientific discourses. But the rationale for building consensus frames is often in apparent dissensus about values and objectives (Candel et al., 2014)—and introducing new wordings might only be window dressing without resolving the underlying conflicts. Moreover, broadly shared themes such as "adaptation" and "resilience" are rather technical and depoliticized concepts, designed to provide openings for interventions in governance processes. Value-laden issues such as structural inequalities and power asymmetries, which are integral parts of the political nature of adaptation, are then pushed to the background in these governance processes (Vink et al., 2013; Hjerpe et al., 2014). Consequently, while knowledge exchange and shared understandings is often the result of transdisciplinary research, it seldom leads to empowerment and actual implementation (Brandt et al., 2013). These so-called consensus frames may lead to abstract agreements but are of limited value in actual implementation.

(4) Fourth, the current emphasis on practice-oriented, transdisciplinary science for adaptation is rather closed, not very reflexive, nor attractive for disciplinary sciences to be involved in. Dovers and Hezri (2010) for example argue that there is a self-referencing (inter- or transdisciplinary) community, creating its own scientific legitimacy. This could be considered as strength, evidencing an "adaptation science" or as weakness, suggesting closedness and the danger of "reinventing the wheel." Yet the disciplinary sciences are vital since they can bring novel theoretical and methodological insights into the climate change adaptation debate. Of course, involving the disciplinary sciences more strongly has been proclaimed by many others and while some early noteworthy successes can be mentioned (e.g., Rayner and Malone, 1998), disciplinary scientists are still reluctant to be involved because of the transdisciplinary ambitions. For example, political scientist Javeline (2014) points out that many of the pressing questions about adaptation are less about science and more about political, social, and economic behaviors and institutions and that, despite being uniquely trained to address questions in these areas, political scientists have thus far contributed hardly anything to the adaptation research agenda. In addition, from a practical point of view, scientific research on adaptation has become dependent on practice not only to be socially relevant as required by funding agencies, but also increasingly through co-funding of private or local governmental actors seeking information that supports their growing concerns about climate change risks.

(5) A final pitfall of transdisciplinary research is the tendency to assume that the programme objectives can be achieved by a one-size-fits-all approach in which stakeholder involvement is central (heuristic: "involve all relevant stakeholders

Box 1 | Transdisciplinarity and co-production: more than just new magic concepts?

In the development of research programmes and projects on adaptation terms such as "resilience," "transdisciplinarity," and "co-design" and "co-production of knowledge" are frequently used. While these terms may play a useful role in forging agreement about strategic directions of these programmes, one may question their usefulness when it comes to implementing specific projects for a specific context. The terms share characteristics with so-called "magic concepts" (Pollitt and Hupe, 2011): *broadness* (covering large domains and having multiple, overlapping, sometimes conflicting definitions), *normative attractiveness* (having a positive connotation), *implication of consensus* (diluting, obscuring, or even denying traditional social science concerns with conflicting interests and logics), and *global marketability* (being well-known and fashionable). Magic concepts can help to set agendas, to provide a vocabulary for debate, and to attract contracts and grants. At the same time, they are neither very precise nor necessarily stable, and do not provide guidance on follow-up action (Pollitt and Hupe, 2011). For developing meaningful practice-oriented projects, more precise descriptions of the problems at hand and the methodologies that can be used to address them are required. For this to evolve, we need better science *on* adaptation.

throughout the process"). In practice, even if there is initial agreement on joint objectives and collaboration, many stakeholders who may be important in theory may delegate the work to staff who appear in the end not to be motivated to become sufficiently involved because of multiple reasons such as lack of time, different perception of project objectives, low expectations about the benefit of participation or simply because they participated in similar activities before and have grown weary of contributing again ("stakeholder fatigue," e.g., see Hedger et al., 2006). Some governance arrangements are designed as open dialogues with stakeholder learning spaces, but do not include the relevant actors with political powers to make decisions. Many transdisciplinary project proposals include plans to engage stakeholders that in practice can fall short of success, because the timing and objectives of the engagement are science rather than policy driven. With lack of evaluation of success of projects afterwards, there is a risk that stakeholder involvement is rhetoric rather than productive in practice (Groot et al., 2014). Working with stakeholders brings the additional challenges of reconciling different time horizons (very short for businesses and policy cycles and long for science) and, in the case of private actors, issues related to the public access of project results. A careful co-design of the project's objectives, timeline, procedures, responsibilities, and outputs tailored to the specific decision-making context would clarify the different actor roles from the start, but is often lacking.

SCIENCE *OF* ADAPTATION: SEARCH FOR DISCIPLINARY PLURALISM

As discussed above, the science *for* adaptation evolves mainly in a transdisciplinary fashion, by analyzing how to address societal adaptation challenges in various real-word contexts using available theories and data to describe and advise policy practice. We postulate that good policy recommendations require linkages between science, policy, and society, but it also requires reflexive distance and scientific evidence to support the advice on how to best adapt to climate change. There are obviously potentially intractable conflicts between the aims of the science *of* adaptation (to better understand) and the science *for* adaptation (to support policy and practice), but too much focus on the science *for* adaptation would be problematic since in the end it should be to a large extent dependent on the science *of* adaptation. The questions posed in the latter might not be immediately socially relevant, but they are necessary to inform meaningful science *for* adaptation. A science *of* adaptation would approach adaptation to climate change as an observable societal act that can be studied from different angles and adopting different disciplinary perspectives, grounded in and requiring expertise from the forefront of both natural and social disciplinary sciences, to really understand some of the fundamental aspects of the adaptation. As illustrated in **Figure 1**, in the context of this paper we specifically imply social science disciplines which have been underrepresented in adaptation research to date. One example is the (*a priori)* need to embark in stakeholder engagement or co-creation processes as a fundamental step in moving adaptation practice. A science *of* adaptation can point out if there are recurring patterns and processes in stakeholder involvement across cases that can determine under which conditions certain types of stakeholder involvement is proven to be most effective to implement measures to adapt, or suggest conditions where no or limited participation is perhaps more effective (see for example Few et al., 2007).

In the context of this paper, we define the science *of* adaptation as a combination of disciplinary research theories and methods, grounded in the classical science traditions, to theorize and test the fundamental assumptions, processes, and principles of adaptation to a changing climate so as to provide an evidence base for the science *for* adaptation. Such endeavor therefore goes beyond merely including (multi)disciplinary sciences in supporting decision making on adaptation. We propose three potential roles for such science *of* adaptation: (1) break through heuristics and clarify key concepts; (2) move toward testing and explanatory ambitions; (3) allow for multiplicity of ontological perspectives and methodological variety.

(1) A science of adaptation would aim to understand the more fundamental scientific questions. Despite 15 years of research we are still unable to conceptually disentangle adaptation to climate change from adaptation to environmental change (Dupuis and Biesbroek, 2013). We hardly know what "successful" adaptation means (Doria et al., 2009), or the conditions necessary or sufficient for evaluating successful adaptation. In addition, although definitions of maladaptation have been provided by different authors (e.g., Swart et al., 2014), it has not been systematically analyzed what it implies in theory and practice, and how it might be avoided in different contexts (Barnett and O'Neill, 2010). Other fundamental questions seem to be ignored altogether:

is adaptation so different from other types of directional change (Chapin et al., 2006)? If so, can we articulate precisely what makes adaptation to climate change so different? If the answer is no, then why are we so vigorously trying to make it into a separate field of research? What does this mean for involving the disciplinary social sciences more actively? Addressing or highlighting these conceptual challenges requires involving the disciplinary sciences more constructively.

(2) A science of adaptation would induce a move from deductive and explorative ambitions toward inductive and confirmatory research designs. Most of the research on adaptation today focussed on small-n case studies, examining a small number of cases in depth to explore why adaptation in that particular case is successful (or not) and, sometimes, which lessons may be applied in other contexts (Ford et al., 2010). Although this type of research has provided valuable insights and some inspirational examples, the context-dependent nature of adaptation makes it difficult to distil, compare, and evaluate insights from such types of studies. Surely, single-n or small-n cases are instructive if proper conditions are met (Flyvbjerg, 2006), but some of the more fundamental questions require other types of research design which are well-known and applied in other areas but not in climate change adaptation. For example, what are the conditions that are necessary or sufficient in explaining why adaptation is or is not successful? When is stakeholder participation in answering this question appropriate and when is it not? Addressing these questions requires new research methods and techniques that have hardly been used in the scholarly community on adaptation today. In addition, some have argued that the move toward explanatory designs is challenging because data sets do not exist, or because of conceptual challenges (Dupuis and Biesbroek, 2013). To move forward in the science of adaptation requires methodological variety and conceptual clarity before comprehensive datasets can be built (Murtinho and Hayes, 2012). Such datasets would allow more active involvement of other sciences. One example for a prospective adaptation research agenda in political science is provided by Javeline (2014): although it is acknowledged by the adaptation research community that adaptation is a political endeavor (Vink et al., 2013), research areas within the political sciences such as comparative politics, public opinion, political partisanship's influence, national security, and others are hardly addressed (for reasons discussed earlier).

(3) A science of adaptation would also more actively engage in debates about the epistemological and ontological underpinnings of the discussion on adaptation, which are currently scarce at best (O'Brien and Hochachka, 2010; Hegger et al., 2012). The value of ontological debates is to better understand the truth-value of existence claims and better understand the multiple ways of knowing. It centers around questions about how to deal with normative ambiguity that is inherent to adaptation practices. How do we perceive the link between climate risk and vulnerability (Dupuis and Knoepfel, 2013)? Transdisciplinary studies include by definition pragmatists who search for, and eclectically combine, existing ideas and theories without considering potential ontological conflicts. By allowing for a science of adaptation, more explicit room for purists' ideas would be opened, and accounting for different ontological perspectives would broaden the scope of what adaptation could look like in practice and how it can be advanced.

CONNECTING SCIENCE *OF* AND SCIENCE *FOR* ADAPTATION: A DIVERSIFIED APPROACH

In this paper, we noted the tendency in current and programmed research on climate change adaptation to move toward a single, transdisciplinary approach with a strong co-production and stakeholder involvement component. We call this the science *for* adaptation. Patt (2013) raised the question: "what if adaptation isn't really a very good science of its own"? We argue that, alone, the current science for adaptation may not really meet the standard of "a very good science of its own." Furthermore, and considering the importance of adaptation as one of the most pressing societal issues (WEF, 2013, 2014), we do believe it can also be scientifically strengthened. We therefore plea for a scientific endeavor that captures and balances both science for and of adaptation. Whether this combination should be called "adaptation science" may not be a very meaningful question from a purely scientific perspective. It may be of practical and linguistic interest, for example when developing specific (new) journals, in the design of academic courses and research programmes, financing disciplinary research projects of adaptation, or even the development of new academic or other institutions.

Rather than suggesting to develop a "science of adaptation" research line in parallel to the current science for adaptation, we here more modestly suggest to correct the growing bias in the current adaptation research programmes and funding schemes toward a better balance between science *for* and *of* adaptation. This would recognize that some distance between these two types of research is needed for reflection, synthesis, and further learning. While we acknowledge that learning by doing in participatory, practice-oriented research is useful and can be productive, we also argue that a better understanding of the underlying theoretical frames and processes can lead to a more effective support to decision-making processes on the longer-term; it is too soon to only focus on transdisciplinary and practice-oriented research. Here, we refer to social science questions about what exactly does adaptation entail, both theoretically and conceptually, enhancing an understanding that may be as—or even more- important than improvements in climate modeling or impact studies for advancing climate change adaptation in practice.

Strengthening the science for adaptation requires overcoming a number of barriers created by the move toward transdisciplinary research and how the research on adaptation has evolved: (1) application of untested heuristics in practice; (2) scientists as problem-solvers; (3) confusion about framing and terminology; (4) unattractiveness for disciplinary researchers, and (5) one-size-fits-all approaches. In particular, we feel that the idea of the transdisciplinary research endeavor will not be sufficiently attractive to involve the disciplinary social sciences. A better understanding is required of the types of knowledge that are needed to support the science for adaptation which, in turn, allow to allocate scientific research funding to disciplinary focussed research projects that may not be of immediate societal relevance. In particular, we propose to give more weight in climate change adaptation research to science of adaptation that would encourage to (1) break through heuristics and clarify key concepts; (2) move toward testing and explanatory ambitions, and (3) allow for multiplicity of ontological perspectives and methodological variety.

A new generation of scholars on climate change adaptation might be able to connect across scientific disciplines, be sensitive to practice-relevant questions, to couple science and practice, and to provide clear and simple stories (Mustelin et al., 2013). They are an integral component for the success of the practice-oriented research endeavor. We envision an important share of the new generation of scholars on climate change adaptation to be generalists, educated to assist addressing real world problems. But this means that there is also an increasing need for a science *of* adaptation—to provide substantive insights and recommendations to support transdisciplinary research. This combination of disciplinary, interdisciplinary, and transdisciplinary research would encourage a broader spectrum of relevant disciplinary sciences to become involved in adaptation science beyond just a transdisciplinary, practice-oriented approach.

If research funding and programming agencies would aim to strike a good balance between a science *for* adaptation and a science *of* adaptation, the societal impacts can be much larger than a sole focus on practice-oriented science, which may lead to a million case studies without necessarily a good understanding of underlying processes or the development of appropriate frameworks and methodologies. We hope that in the new Interdisciplinary Climate Studies journal of Frontiers in Environmental Science there will be room for both a science *for* adaptation and a science *of* adaptation.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 25 April 2014; accepted: 14 June 2014; published online: 02 July 2014.
Citation: Swart R, Biesbroek R and Capela Lourenço T (2014) Science of adaptation to climate change and science for adaptation. Front. Environ. Sci. ***2****:29. doi: 10.3389/fenvs.2014.00029*
This article was submitted to Interdisciplinary Climate Studies, a section of the journal Frontiers in Environmental Science.

CHAPTER 3: UNCERTAINTY AND ADAPTATION DECISION-MAKING

Publication II - Making adaptation decisions: the far end of the uncertainty cascade

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This paper is published in the proceedings of the *Impacts World 2013 International Conference on Climate Change Effects* and should be referenced as: Capela Lourenço, T., Rovisco, A., Groot, A., van Bree, L., Street, R., Garrett, P. and Santos, F.D. (2013) Making adaptation decisions: the far end of the uncertainty cascade. Impacts World 2013, International Conference on Climate Change Effects, Potsdam, 27 -30 May 2013.

Impacts World 2013, International Conference on Climate Change Effects,
Potsdam, May 27-30

Making adaptation decisions: the far end of the uncertainty cascade

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Abstract

The now convincing evidence that climate is changing brings about additional sources of uncertainty for adaptation decision-makers across scales (i.e. local to international) and capacities (e.g. policy-makers, practitioners). Uncertainty is associated with limitations on the knowledge of a relevant system. The scientific enterprise thrives on uncertainty and on the quest for knowledge. But for adaptation, as for most all high-stake, potentially transformative and financially sensitive decisions, there is a clear need for a robust evidence-base ('a figure to put on the decision') placing adaptation decisions at the far end of a complex cascade of uncertainties. Taking model-based decision support as example, uncertainty can spur from the choice of socio-economic scenarios (e.g. SRES), climate models (e.g. HadCM), biophysical impacts models (e.g. SWAT), integrated assessment models (e.g. IMAGE), vulnerability assessments (e.g. DIVA), to end up in the decision-making process itself. Climate impact and more recently adaptation research communities have focused their efforts in improving the utility of their results by reducing uncertainties in conceptual and modelling frameworks. But little attention has been given to understanding if these efforts have been successful in supporting the sort of complex decisions they aim at ('are adaptation decisions being made?'). Recent literature, mostly related to high-end climate change scenarios has called the attention to some key gaps. Firstly, the need of innovative strategies and end-user involvement in the development of uncertainty-management methods; and secondly, the need to frame these within a broader sorting of decision types systematizing them into support frameworks. This paper reports on work carried out in the CIRCLE-2 Joint Initiative on Climate Uncertainties leading to the publication of a 'lessons learned' guide to uncertainty, and stimulated from real case-studies where dealing with uncertainties in adaptation decision-making processes was successfully accounted for (or identified but failed).

Keywords: Adaptation, Climate Change, Decision-making, Uncertainties

1 Introduction

Decisions associated with planning and managing the environment are severely affected by uncertainty (Dessai & Hulme 2007) bringing about complexity for both scientists and decision-makers (Hanger et al. 2012). However, in many circumstances decisions must be made before robust evidence-base is available or before uncertainties can be reduced (Walker et al., 2003; van der Sluijs et al., 2008).

Walker et al. 2003 defined uncertainty as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system". Thus, uncertainty is also a natural product of the scientific process where typically questions arise as to what information can be considered valid and reliable (van der Sluijs et al. 2008; Lemos & Rood 2010). Even though progress has been made in quantifying and characterising the uncertainty relevant for climate adaptation planning not much progress has been made in reducing it (Mearns 2010).

For quite some time the scientific community has been debating whether the focus should be in reducing uncertainty or whether it should be to embrace and deal with uncertainties in decision making processes (Mearns 2011). Several scientists advocated the need to reduce uncertainties in climate models and projections since these are being increasingly procured by decision-makers and seem essential in assessing the impacts of climate change and the development of adaptation strategies (Gagnon-Lebrun & Agrawala, 2006; Füssel, 2007; Shukla et al. 2009; Hawkins & Sutton 2010). However, prospects of fully reducing uncertainties are very limited and the potential for climate science to achieve these reductions will only be through contributions associated with internal variability and model uncertainty, and not the uncertainty associated with future emissions of greenhouse gases (Hawkins & Sutton 2010), since these are mostly policy dependent. In any case, the argument that decision-makers are increasingly demanding such information is contested by Tribbia & Moser (2008) and Hanger et al. (2012) which demonstrated that decision-makers do not feel that there is a need for more information, but rather for better access to and easiness of use of the existing data. On the other hand, more and/or better information may not be as significant to decision-makers as has been thought and efforts should focus on integrating available information in the decision-making process (Tribbia & Moser 2008).

In fact, Lemos & Rood (2010), argue that "there is an uncertainty fallacy, that is, a belief that the systematic reduction of uncertainty in climate projections is required in order for the projections to be used by decision makers" and others state that effective and successful adaptation planning and strategies can be developed and implemented without being significantly limited by the uncertainties present, e.g., in climate predictions (Lempert et al. 2004; Hulme & Dessai 2008; Dessai et al. 2009; Lempert & Groves 2010; Walker et al. 2003; Smith et al. 2011).

Furthermore, there are other barriers to decision-making besides uncertainty (Moser & Ekstrom 2010; Tompkins et al. 2010; Eisenack & Stecker 2011; Smith et al. 2011; Pidgeon & Fischhoff 2011; Runhaar et al. 2012) and decision-makers should examine "the performance of their adaptation strategies/policies/activities over a wide range of plausible futures driven by uncertainty about the future state of climate and many other economic, political and cultural factors" (Dessai et al. 2009).

This paper addresses a primarily the Conference question 'How certain are we?' and aims to present the work of the CIRCLE-2 Joint Initiative on Climate Uncertainties, leading to the publication of a science-practice oriented book on how climate uncertainties have been dealt with and accounted for (or failed to) in real-life adaptation decisions. The Initiative was set up in 2011 under the umbrella of the FP7 CIRCLE-2 ERA-Net (www.circle-era.eu). It aims at the development of a network of researchers and practitioners involved in dealing and communicating climate change related uncertainties in support of adaptation decision-making processes. This article will report on one of the chapters of that book and on the supporting case-study analytical work.

2 Methods

Work carried out involved four steps, of which the first three were implemented during 2012 and the final one will be finalised by mid-2013: (i) a world-wide call for practical case-study examples of science-supported adaptation decision-making process and how these dealt with climate-related uncertainties; (ii) a review and selection of examples; (iii) a set of individual interviews with researchers and decision-makers involved in the selected cases; and (iv) the review, critical analysis and publication of the empirical data obtained in the previous steps.

The first step consisted on a widely disseminated call for case-studies using a pre-defined template. In it, interested applicants were introduced to the initiative, objectives and selection process and asked to describe their case in terms of general information (origin, scale, sectors, type of organisations involved) and more specifically on what kind of climate information was used, which methods to deal with the cascade of uncertainties were applied, what were the expected outcomes from the decision-making process, and generally what went well, what not and what kind of lessons could be extracted to support similar decision needs.

The second step was to select a set of representative cases. The selection was conducted by a group of experts, all of them members of the CIRCLE-2 Joint Initiative. Previous agreement defined that the final selection had to include cases that could tentatively help to reply to the question '*have better informed adaptation decisions been taken because uncertainties were conscientiously addressed?*' Other criterions for selection included the need that each case was related to a real adaptation decision process, the degree of involvement of stakeholders and decision-makers in the research process, and diversity in scope (geographical, sectorial and scale). E-mail contacts with authors of the submitted case-studies were conducted during this step in order to clarify doubts and specific questions about the work described in their responses.

Step three involved individual phone interviews with the authors (mostly researchers) and the decision-makers (policy or practitioners in most cases) of all the selected cases. The interviews were conducted by the initiative experts with the assistance of a professional science storywriter. These interviews had two objectives: (i) to clarify specific doubts left open by the template and subsequent contacts and (ii) to further investigate the researchers' and decision-makers' perspectives on how the adaptation decisions were (or not) affected by the inclusion, in the decision support, of methods to deal with (and/or communicate) uncertainties.

Finally, step four is still underway and consists in the application of a qualitative Common Frame of Reference (i.e. common definitions, understandings, disagreements and recommendations) to the analysis of selected cases and the extraction of key lessons to support complex adaptation decision-making processes. For each of the cases, this reference framework looks into: (a) the adaptation decision-making objectives[1] (Kwakkel et al. 2011); (b) the research approach to the decision-making support (i.e. development and use of model or non-model based evidence) (Dessai et al. 2009); (c) the direction of the approach regarding Climate Change Impacts, Vulnerability and Adaptation (CCIVA) assessments (i.e. predictive top-down or robustness/resilience bottom-up) (Dessai & van Der Sluijs 2007); (d) the uncertainty level addressed (i.e. statistical; scenario; recognised ignorance) (Walker et al. 2003); and finally (e) the decision-making outcome (i.e. the decision made in relation to the original objectives of the decision-maker). This paper reports only on points (a) through (d) leaving out the analysis of the decisions made in each case-study.

3 Results and discussion

Responses to the survey in step one yielded a total of 27 validated replies from 15 different countries. Despite some bias towards Water Management, Infrastructure and Disaster Risk Reduction (DRR) projects, there was a diverse sectoral distribution of cases covering a wide range of decision-making processes. Only 6 cases (22%) reported a single-sector focus, while 21 reported a multi-sector approach and of those 2 reported efforts on all of the sectors (in some cases other sectors not described in the template were reported). Submitted cases presented a clear geographical bias towards Europe (almost 90% of cases), developed countries (more than 95% of cases) and sub-national scales (over 95% of cases).

[1] This Common Frame of Reference distinguishes between 3 types of objectives for an adaptation decision: (a) Normative or Regulatory, associated with governance actions that aim to establish a standard or norm; (b) Strategic or Process-oriented, associated with the identification of long-term or overall aims and the necessary setting up of actions and means to achieve them; and (c) Operative or Action-oriented, related to the practical actions and steps required to do something, typically to achieve an aim.

All of the organisations responsible for the adaptation decisions were public, stated owned or a mix of public-private institutions. No completely private case replied to the survey. Table 1 presents the total number of cases submitted, as well as their geographical, sectoral, scale and type of organisation distribution. Highlighted cases in table 1 represent those selected for further analysis in step two.

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Table 1 - Total number of received case-studies according to their geographical, sectoral, scale and type of organisation distribution.

Case ID	Origin	Sector										Scale				Type of organisation			
		Water Management	Agriculture & Forestry	Biodiversity	Coastal areas	Marine & Fisheries	Health	Infrastructure	Financial	Disaster Risk Reduction	Other(s) - as submitted	International	National	Regional	Local	Private	Public	State owned	Non-profit org.
001.1	Austria							●					●				●		
001.2	Austria		●											●				●	
002.1	Canada	●						●					●					●	
003.1	Greece	●	●		●	●	●		●				●				●		
004.1	Netherlands										Multi-sector focused on spatial planning			●	●		●		
004.2	Netherlands	●					●						●				●		
005.1	Portugal	●						●						●				●	
005.2	Portugal	●						●	●	●			●						●
005.3	Portugal				●			●	●	●					●		●		
006.1	Spain	●								●			●				●		
006.2	Spain	●	●											●			●		
007.1	Sweden	●								●	Dam safety		●			●	●		
007.2	Sweden		●										●			●	●		
008.1	United Kingdom	●		●	●						Ecosystem services and land use planning		●				●		
008.2	United Kingdom	●	●	●	●	●	●	●	●	●	Tourism		●				●		
008.3	United Kingdom	●													●		●		
008.4	United Kingdom	●		●			●	●	●	●	Policy			●		●	●		
009.1	Hungary	●						●					●				●		
010.1	Ireland							●		●			●				●		
011.1	Germany	●	●	●	●			●	●						●	●	●		
011.2	Germany							●							●		●		
011.3	Germany	●	●	●			●				Regional planning			●			●		
012.1	France			●				●		●					●		●		
013.1	Kiribati										Climate Change displacement	●					●		
014.1	Finland	●	●	●	●	●	●	●	●	●	Energy supply, Culture and Insurance				●		●		
014.2	Finland	●						●		●	Urban planning			●		●	●		
015.1	New Zealand							●		●					●		●		
Total		**17**	**8**	**7**	**6**	**3**	**6**	**15**	**8**	**12**	**9**	**1**	**12**	**7**	**8**	**5**	**23**	**3**	**1**

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From the 27 submitted case-studies, 12 were selected for analysis. Table 2 depicts how the authors of those cases described: (i) the methods used to deal with uncertainty (after Dessai & van der Sluijs 2007); (ii) attempts made to change the decision-maker's initial perspectives on uncertainty, and if so what methodologies were used; and (iii) if decisions (and which) were taken based on the information provided by science.

Nine out of the 12 selected cases reported the use of Expert Elicitation (EE) and Stakeholder Involvement (SI) as methods applied to deal and communicate uncertainties. In fact, these 9 cases applied both methods in conjunction and there was no single case reporting the use of just one of these 2 methods. Only 3 cases did not report the use of such methodologies. Yet, in these cases the use of meetings, workshops and interviews as a mean to change decision-makers perspectives about uncertainty was reported.

Eight of the selected case-studies reported the use of Sensitivity Analysis (SENS) and 6 the use of Scenario Analysis (SA) as methodological approaches to uncertainty. Probabilistic multi-model ensemble (PMME) methods were only reported by 4 of the cases and all remaining methods were described either by 1 or 2 case-studies.

All reported examples applied at least 2 methods and except for 2 cases that reported only the use of EE and SI, all others used 3 or more methods to inform adaptation decisions. The interviews conducted in step 2 with both researchers and decision-makers clarified that this is often related to the fact that each project is usually dealing with multiple adaptation-decisions, sometimes at different scales and areas.

Regarding actual decisions in each of the case-studies, only 2 reported that no decisions were made (yet) while 1 reported that the decision(s) had been delayed. Although it is not the focus of this paper, table 2 briefly presents some of the types of adaptation decisions that were made and that could be traced back to - or analysed in light of - the uncertainty management or communication methodologies that were applied to the decision-making support process.

Another interesting feature of this empirical information is the fact that all cases reported that the science advice conscientiously used some type methodology to change the decision-makers perspectives about what uncertainty means, and how it may (or may not) affect their decisions. Nevertheless, caution must be placed in the analysis since the survey process (e.g. the template for reporting examples) may have biased the type of respondents towards researchers that already conscientiously apply this sort of approaches in their research designs.

Table 2 - Selected case-studies for analysis including reported: (a) description of the methods used to deal with uncertainty; (b) usage of methods to change decision-maker's perspective on uncertainty; and (c) decisions taken (or not).

Case ID	Methods used to deal with uncertainty													Methods used to change perspectives on uncertainty	Decisions taken?
	SA	EE	SENS	MC	PMME	BM	NUSAP	FZ/IP	SI	QA/QC	EPP	WC/SS	Other(s)		
001.1		●	●			●			●					Meetings and workshops	Improve railway track drainage. Include climate change into company's long-term strategy. Invest in a monitoring system.
002.1	●	●	●		●				●					Meetings	Use multiple-scenarios in current analysis of climate change impacts on the company's infrastructures and pursue further in-depth research.
004.1	●	●	●						●		●			Workshops	No.
004.2		●							●					Workshops and questionnaires	No.
005.1	●	●							●					Meetings and workshops	Establish cooperation protocols with external stakeholders. Withhold investments in nanofiltration systems. Delay investment decision on protection measures against forest fires.
008.2	●	●	●			●	●		●	●	●			Workshops and questionnaires	Officially use evidence in national and local support of adaptation decision-making (policy and planning).
008.3				●	●									Meetings and workshops	Recommend and provide guidance on the use of probabilistic climate change information in water resources plans.
009.1		●	●		●			●	●					Meetings	Invest in new flash flood monitoring systems. Install new treatment plant. Shut down small groundwater abstractions and concentrate in larger water sources. Develop a regional water pipeline.
010.1			●									●		Meetings	Move from deterministic to robust approaches on the design of structural flood defences.
011.2	●	●	●					●	●			●	Causal and Fuzzy cognitive mapping	Workshops	Decision was delayed.
012.1		●							●					Meetings and public consultation	Use a 'low regret' approach by restoring sand dunes as flood defences instead of dykes and relocating road landward.
015.1	●		●		●									Interviews and workshops	Include evidence in the review of flood risk management plan.
Total	**6**	**9**	**8**	**1**	**4**	**2**	**1**	**2**	**9**	**1**	**2**	**2**	**1**		

Abbreviations: SA - Scenario analysis ('surprise-free'); EE - Expert elicitation; SENS - Sensitivity analysis; MC - Monte Carlo; PMME - Probabilistic multi model ensemble; BM - Bayesian methods; NUSAP - NUSAP / Pedigree analysis; FZ/IP - Fuzzy sets / Imprecise probabilities; SI - Stakeholder involvement; QA/QC - Quality assurance / Quality checklists; EPP - Extended peer review (review by stakeholders); WC/SS - Wild cards / Surprise scenarios.

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Together with the individual interviews, the application of a Common Frame of Reference to the selected case studies provides an initial approach to the understanding of how uncertainty was dealt with and communicated in each of the cases. This means reflecting upon how the adaptation decision-making needs (or questions) were methodically addressed by research and, in turn, what were the outcomes in terms of actual decisions made (or not). Table 3 presents some of the preliminary results of the systematic application of the Common Frame of Reference to the analysis of each of the selected case studies. It presents the nature of each case's decision-making objectives and the approaches followed by researchers to support those decisions (i.e. modelling; direction of the causal chain of evidence; and levels of uncertainty addressed). This analysis is currently being undertaken in step 4 of the previously described methodology.

Table 3 - Analysis of the selected case-studies using the Common Frame of Reference, including: (a) the nature of the decision-making objectives; and (b) the type of approaches used by research.

Case Study ID	a. Decision-making objective(s)			b. Research approach to:						
	Normative or Regulatory	Strategic or Process-oriented	Operative or Action-oriented	Decision-making support		CCIVA assessment & decision-making strategy		Uncertainty level		
				Model based (quantitative)	Non-model based (qualitative)	Top-down & predictive oriented	Bottom-up & robustness / resilience oriented	Statistical	Scenario	Recognised ignorance
001.1		●	●		●	●		●		
002.1		●		●		●		●		
004.1		●		●	●	●			●	
004.2	●				●		●		●	
005.1		●	●	●	●	●	●		●	
008.2	●			●	●	●		●	●	
008.3	●		●	●		●		●		
009.1		●		●	●	●	●		●	
010.1		●		●			●		●	●
011.2		●			●		●		●	●
012.1	●				●		●			●
015.1		●		●	●	●	●		●	

Regarding the objectives of the analysed practical decision-making processes there is a bias in favour of strategic or process-changing oriented examples (8 out of 12) against normative (4 out of 12) and operative decisions (3 out of 12). Despite the existence of several cases addressing multiple decisions, only 3 cases (from Austria, Portugal and the UK) appear to deal with decisions of different fundamental nature. While the first deals with operative and strategic decisions, the later with regulatory and operative decision processes. The relatively small number of analysed cases raises the question whether it is possible to capture a significant range of types of decision-making objectives or if there are 'other' types that may have been left out. Since there was no pre-judgement of cases, that is, there was no limitation to the submission of cases according to their type of decision objectives there is still room for further investigation using all the submitted cases, including those that were not selected for analysis through this common framework.

In terms of the research approach to the decision-making support results are somewhat balanced with the analysis showing that 4 cases used only modelled evidence, 4 used only non-model information and 5 used both approaches. In the latter ones, the fact that often multi-sector and multi-scale decision-processes are acknowledged indicates that projects are also using multiple and diverse approaches to inform decisions.

When it comes to the direction of the CCIVA assessment chain followed by the selected cases, there are 5 examples that used a marked top-down and optimization focused approach, while 4 applied a fully robustness-based bottom-up approach. Only 3 cases appear to have made used of both approaches, although it is not easy to grasp if simultaneously or in different phases of the project.

Regarding the uncertainty level addressed in the support to decision-makers, no single case demonstrably dealt with all 3 levels (from statistical to recognised ignorance, following Walker et al. 2003). Only 1 case (French) dealt exclusively with this higher level of uncertainty, while 3 cases only with statistical uncertainty. Eight cases out of the 12 dealt with or communicated uncertainties along the scenario level although 3 of them did it in combination with other levels (1 with statistical and 2 with recognised ignorance).

4 Conclusions

It has been argued that further research is required to develop methods that evaluate planned and unplanned adaptations and to locate adaptations in the landscape of decision-making and risk (Tompkins et al. 2010). Recent literature, mostly related to high-end climate change scenarios (i.e. above 4ºC), has called the attention to some key gaps and requirements of this analysis. It has been suggested that rather than being unable to make decisions under uncertainty, what has been missing is the deployment of innovative decision-making frameworks to deal with uncertainties prompted by climate adaptation assessments (Hallegatte 2009; Smith et al. 2011). The application of a Common Frame of Reference in the analysis of different types of adaptation decision objectives and of the research approaches used to inform them provides a further step in the understanding of how to design and apply such novel decision-making frameworks (e.g. the role of different information needs vs. different decisions approaches).

Although the empirical analysis described in this article is not sufficient to draw generalised frameworks for all types of adaptation decisions (site- and culture-specificity still prevails), this preliminary work makes a move towards key adaptation research and decision-making needs. By systematically collecting, selecting and analysing concrete examples where science was called upon to support real adaptation decision-making processes, and did so using uncertainty management and communication approaches, we move a step closer in the understanding of two relevant questions. Firstly, how is science dealing with (and communicating) uncertainty in light of what the adaptation decision objectives and needs are. And secondly, what have been the outcomes of such approaches in terms of concrete decisions that were made (or not) and how did the use of such methodologies improve the support to those decision processes ('are better informed adaptation decisions being made?'). The systematization presented here requires further development and enrichment but the gradual emerging of case-studies where concrete adaptation decisions are made provides a required stepping-stone towards clear guiding frameworks to both decision-makers and researchers.

5 Acknowledgements

The work presented in this paper was supported by the CIRCLE-2 Joint Initiative on Climate Uncertainties and its network members. The initiative is financially supported by the Calouste Gulbenkian Foundation - Portugal and by the institutions where network members are affiliated. The authors wish to thank all the authors and decision-makers involved in the submission and review of case-studies.

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Publication III - Showcasing practitioners' experiences

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This book chapter is published in the Adapting to an Uncertain Climate: Lessons from Practice book and should be referenced as: Groot, A., Rovisco, A. and Capela Lourenço, T. (2014) Showcasing practitioners' experiences, *in* Capela Lourenço T., Rovisco, A., Groot, A., Nilsson, C., Füssel, H-M, van Bree, L. and Street, R. (Editors) (2014) *Adapting to an Uncertain Climate: Lessons from Practice*. Springer, the Netherlands, ISBN: 978-3-319-04875-8, 182pp.

Chapter 4
Showcasing Practitioners' Experiences

Annemarie Groot, Ana Rovisco, and Tiago Capela Lourenço

Key Messages

Twelve real-life cases show how policy-makers, decision-makers and researchers have struggled together to deal with uncertainty in adaptation decision-making. Some key features are as follows:

- Most real-life cases conscientiously addressed uncertainties related to the use of scenarios. Few cases dealt with statistical uncertainty and /or recognized ignorance.
- In all cases a combination of multiple methods is applied to address uncertainty. In most of the cases these include expert elicitation, stakeholder involvement and sensitivity analysis.
- The cases all show that conscientiously addressing uncertainty had an effect on the adaptation decision taken and/or changed attitudes to climate change adaptation.
- Most cases show a clear shift in thinking from a deterministic or 'single optimal solution' approach to adaptation towards a flexible, robust and no-regret approach.

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T. Capela Lourenço et al. (eds.), *Adapting to an Uncertain Climate: Lessons From Practice*, DOI 10.1007/978-3-319-04876-5_4,

4.1 Introduction

This chapter describes real-life cases showing how policy-makers, decision-makers and researchers have struggled together to deal with uncertainty in adaptation decision-making (Fig. 4.1). We selected these case studies through a world-wide call for practical examples of adaptation decision-making processes and dealing with climate-related uncertainties. Out of the 27 real life stories, that were submitted in a prescribed format, 12 illustrative cases were selected by a group of experts, all of them members of the CIRCLE-2 Joint Initiative on Climate Uncertainties.[1] The key selection criteria were whether the story increased understanding of handling uncertainty in adaptation planning and implementation, and whether the case showed the impact of conscientiously addressing climate uncertainties on the decision taken. Other criteria for selection included: the link to a real adaptation decision-making process, the involvement of different stakeholders, and diversity in scope (geographical, sectorial and scale).

Despite some bias towards Water Management, Infrastructure and Disaster Risk Reduction projects, the cases show a wide range of decision-making processes to address climate change impacts. Only two cases show a clear single-sector focus, while all others report a multi-sector approach involving agriculture, health, biodiversity, energy and finance. All the case study initiatives are publicly funded and present a clear geographical bias towards Europe (10 cases out of 12). This is due to the fact that although we strived for an open submission of case studies and different international networks and websites were used, we mainly approached potential authors via the European network CIRCLE-2, different European research programmes, and national research programmes such as Knowledge for Climate (The Netherlands), Climate Change-Snowll (Austria) and Klimzug (Germany). Five cases describe how uncertainty is addressed at the national scale, two cases at the sub-national scale and five at the local scale (see Table 4.1). Since adaptation is a relatively new field, most of the decision-making processes deal with (policy) plans, while the actual implementation is still some years down the line. Consequently, the uncertainties dealt with in the cases are predominantly related to assessment of climate change impacts and vulnerability. Very few cases explicitly address uncertainties as to the appraisal of adaptation measures or implementation of adaptation.

The stories are constructed on the basis of interviews with the main decision-maker and the principal scientist involved, together with information on the case study provided in the submission stage. Each description highlights the challenge the decision-maker was facing, the types of climate uncertainties addressed, methods that are used to deal with uncertainties and the final decisions taken. All case studies show how the process of conscientiously addressing climate uncertainties has affected these decisions. Two types of decision making are distinguished

[1] This initiative is a coordinated transnational funding effort, within the scope of CIRCLE-2, aiming at sharing and advancing scientific knowledge and practice on dealing and communicating climate and climate change uncertainties in support of adaptation decision-making. More information on the Initiative is available at: http://www.circle-era.eu/np4/P_UNCERT.html

Fig. 4.1 Real-life cases and their geographic location

Table 4.1 Selected case studies according to their geographical location, sector, scale and type of decision-maker distribution

Case	Country	Sectors and Domains	Scales			Decision maker	
			National	Regional	Local	Private	Public
Water Supply Management in Portugal (4.2.1)	Portugal			•			•[a]
UK Climate Change Risk Assessment (4.2.2)	United Kingdom		•				•
Water Resources Management in England and Wales (4.2.3)	United Kingdom				•		•
Water Supply in Hungary (4.2.4)	Hungary		•				•
Climate Change and Health in The Netherlands (4.2.5)	Netherlands		•				•
Flood Risk in Ireland (4.2.6)	Ireland		•				•
Coastal Flooding and Erosion in South West France (4.2.7)	France				•		•

Québec Hydro-Electric Power (4.2.8)	Canada													•			•[a]
Austrian Federal Railways (4.2.9)	Austria												•				•
Dresden Public Transport (4.2.10)	Germany														•		•
Hutt River Flood Management (4.2.11)	New Zealand														•		•
Communication of Large Numbers of Climate Scenarios in Dutch Climate Adaptation Workshops (4.2.12)	Netherlands													•	•		•
Total		**7**	**2**	**3**	**2**	**1**	**2**	**10**	**1**	**4**	**1**	**1**	**5**	**3**	**5**	**0**	**12**

[a]State-owned

i.e. strategic and operational. Strategic decisions are fundamental and directional, and over-arching. Operational decisions, on the other hand, primarily affect the day-to-day implementation of strategic decisions. While strategic decisions usually have longer-term implications, operational decisions usually have immediate (less than 1 year) implications.

4.2 Real Life Case Studies

4.2.1 Water Supply Management in Portugal

Country: Portugal

Sector: 

Scale: Regional

Organisation: Public (State-owned)

Decision-type: Strategic

Key Messages

This study examined a variety of uncertainties to determine the vulnerability of a Portuguese water supply company to climate change and developed an adaptation strategy to deal with these vulnerabilities.

Key messages from the project were:

- Decision makers and stakeholders needed to be continuously involved for the success of the project. A high level of trust, generated by time-consuming engagement between the parties was necessary to deal with different views on the topic, and the company's confidential data and internal processes.
- Transferability of know-how on the topic between practitioners and researchers was critical and organisations should be able to share this knowledge.
- Quantifying cumulative uncertainty was achievable and important to support decisions, when clear criteria were agreed from the start and properly communicated.

Background

Empresa Portuguesa das Águas Livres (EPAL) is a Portuguese state-owned water utility company. It supplies about three million people living in 35 municipalities on the north bank of the Tagus River, representing more than a quarter of the Portuguese

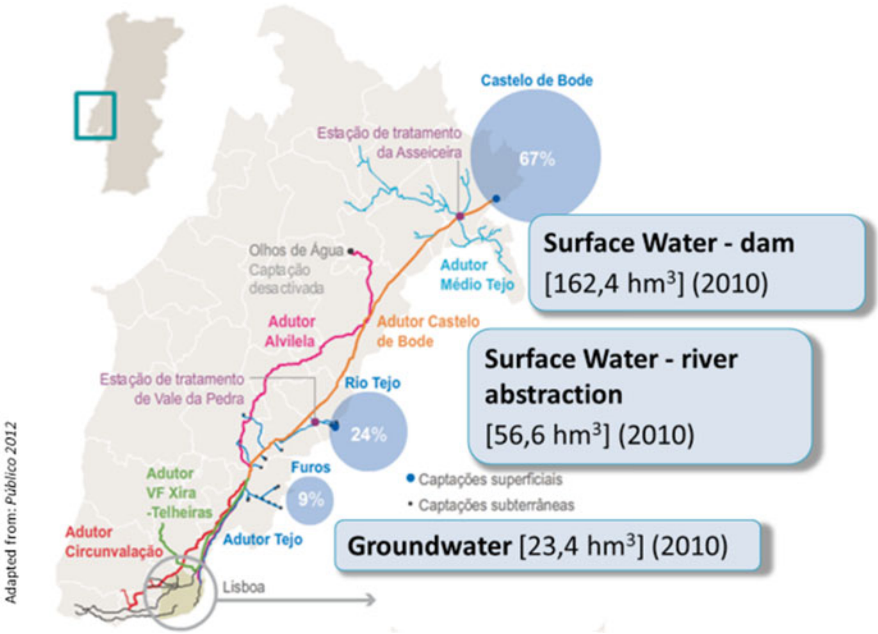

Fig. 4.2 EPAL's geographical system

population. It has three main sources of water: a large reservoir as the prime water source (67 %), the Tagus river (24 %) and groundwater from several boreholes (9 %). Further details are given in Fig. 4.2.

The purpose of the project was to: (i) assess potential climate and demand changes in the geographical area served by the water utility; (ii) identify climate change impacts on the company's water sources; (iii) assess system vulnerabilities, and (iv) identify and appraise a set of potential adaptation options and measures.

The project originated within the company's executive board, because the water sector is seen as one of those potentially most affected by climate change in Portugal. EPAL is conscious of its responsibilities to take climate change into consideration because its main aim is "to supply water, now and in the future, every day, all year round, with the necessary quality and at an acceptable cost". The project began in October 2010 and ran until May 2013.

Coordination of the project was provided by the Faculty of Sciences of the University of Lisbon and involved three other Portuguese universities. From the company's side, there was involvement from EPAL's technical and management staff (one project management committee and one advisory committee) providing company systems data and feedback on the results from the demand scenarios, impact models and other scientific information. Out of 100 of the company's key

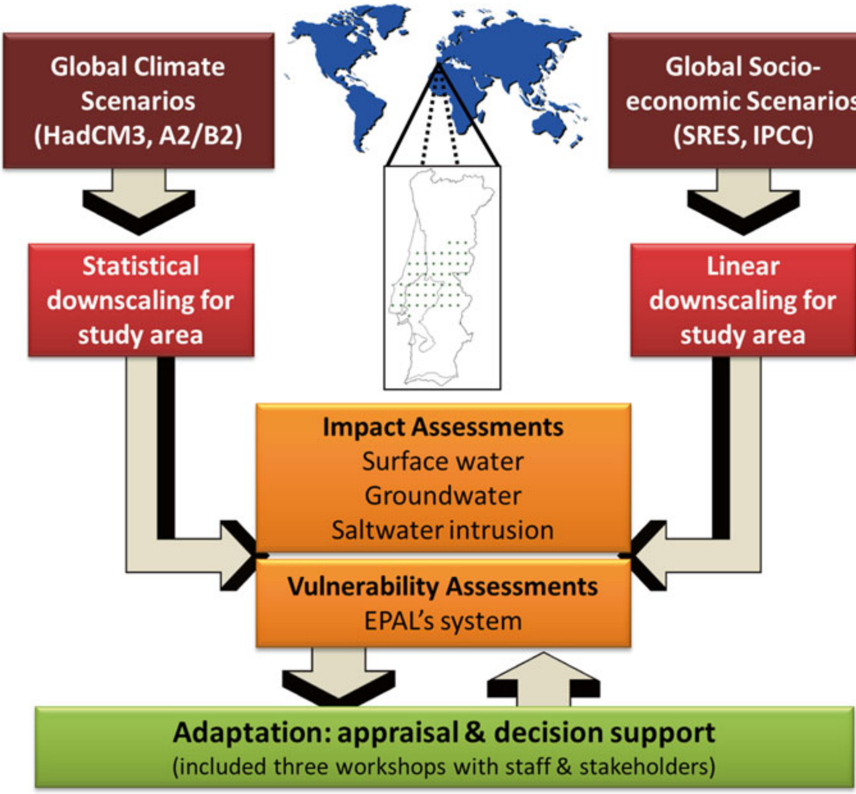

Fig. 4.3 Project general methodology. Top-down and bottom-up approach

external stakeholders (e.g. governmental, regulator, shareholders, clients, NGOs, utilities) about 20 were invited to specific meetings.

Process

The project methodology is shown in Fig. 4.3. Focussing on the development of an adaptation strategy, the project initially reviewed existing global climate and socioeconomic scenarios and downscaled these to suit the company's geographical and time scales. In the past EPAL has considered non-climatic information, such as changes in demographics, and projections on water availability have been incorporated into the project's impact assessments on surface and groundwater resources. In this study scenarios have been utilised. These include climate scenarios (e.g. precipitation) affecting water supply, and socioeconomic scenarios (e.g. demographics) affecting demand. Using these scenarios, impacts

Fig. 4.4 EPAL's Adaptation workshop

on surface water sources, groundwater sources and salt-freshwater interfaces in estuaries were modelled in terms of water quantity and quality. Vulnerability was then assessed by analysing EPAL's capacity to adapt to the potential impacts.

Climate data used

- Interpolated data from European Climate Assessment & Dataset with a grid of 25 × 25 km
- NCEP reanalysis data for calibration and model validation
- Coupled atmosphere-ocean general circulation model (HadCM3) downscaled using a generalised linear model
- Climate change storylines with quantitative information for socio-economic scenarios A2 and B2 (SRES) to the middle and end of century.

Three workshops were held where the results were presented, discussed and some decisions were validated. These meetings aimed to analyse the main results of the project in terms of potential impacts and adaptation measures, identifying potential synergies, conflicts and trade-offs between different alternatives and different stakeholders (Fig. 4.4).

In the last workshop, each potential impact was labelled with a level of scientific confidence (inversely correlated with uncertainty level) in order to better support the decision. To prioritise the adaptation measures for each potential impact and vulnerability, a gaming-like approach was developed. Participants were divided into smaller groups and had to choose from a set of adaptation measures (in the form of adaptation cards, previously co-created and characterised together with EPAL staff via a parallel participatory approach that focused on the adaptation objectives) and discuss the final results.

Overal, over 50 of EPAL's staff and about 20 different external stakeholders participated in the workshops. Contact is being maintained with a sample of these institutions to obtain their feedback and further understand their influence on EPAL's adaptation processes. The majority of the adaptation measures, for example the reduction of pollution in aquifers, need the support of external stakeholders, and the feasibility of measures is being discussed with them.

Continuous interaction with the two internal project committees was designed, among other objectives, to help EPAL's staff and stakeholders understand the meaning of uncertainty in the context of climate adaptation decision-making.

Uncertainty Assessment

Within each project phase different levels of uncertainty were acknowledged and considered for each of the project's activities:

Example of handling uncertainty in hydrological impact modelling using a sensitivity analysis

EPAL is concerned that the freshwater-saltwater interface along the Tagus River estuary could reach its abstraction point at Valada (about 32 km upstream) through a potential combination of reduced river discharge, sea level rise and salinity increases. This would either require the implementation of adaptation measures such as nanofiltration, or the abandonment of the facilities. Past assessments place the interface 15 km downstream of EPAL's abstraction point and a numerical simulation model (CE-Qual-W2) was used to evaluate the potential impacts. However, consultation with the company's experts revealed that the complexity around the river-estuary-sea system created extra uncertainty and reduced their confidence in the model results. A sensitivity analysis using additional model runs was undertaken and results supported, with a high level of confidence, that significant salt water intrusion is not to be expected. Thus, the companies' decision was to not advance with specific adaptation measures at this time.

- Selection of scenarios,
- Socioeconomic data downscaling,
- Climate data downscaling,
- Hydrological and hydrogeological impact modelling,
- Vulnerability assessments,
- Adaptation options appraisal.

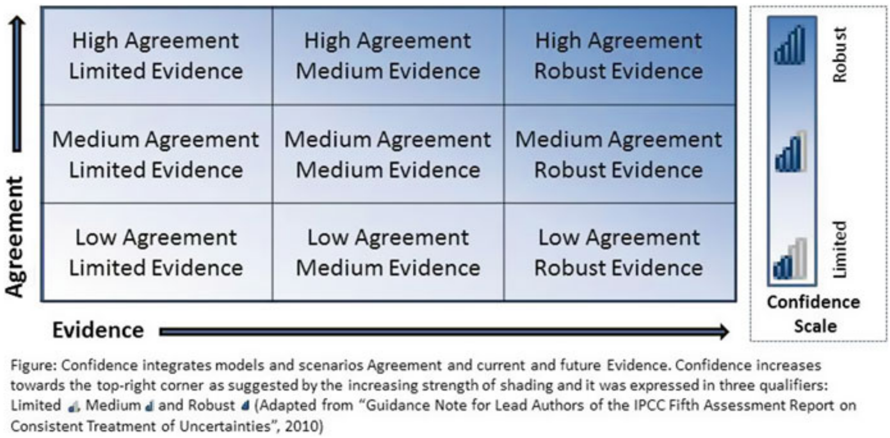

Fig. 4.5 Confidence levels used to communicate uncertainties to decision-makers

Based on current adaptation literature, uncertainties within these activities were dealt with in the following ways:

- Scenario analysis,
- Expert elicitation,
- Sensitivity analysis,
- Stakeholder involvement,
- Extended peer review (review by stakeholders).

From the beginning, the various scientific teams were asked to qualify the uncertainties in their results. Each potential impact was then communicated and associated with a level of confidence derived from a balance between the level of agreement (with other comparative studies) and the level of evidence (statistic robustness of models; quality of observed data) (Fig. 4.5).

The uncertainties associated with the impact of competition between EPAL and other organisations on water resources were not taken into account in a quantitative way (i.e. via models), but addressed through the involvement of stakeholders and expert elicitation of 'what if' issues.

Effect of Uncertainty on Decision–Making

From the start of the project it was clear that not all of EPAL's staff involved had the same attitude to the climate change topic and level of confidence on the potential results of the vulnerability assessment. This is partly because they come from different areas within the company and so have different perspectives regarding the role of risk and uncertainty in operational and strategic decisions. In practical terms this meant that some EPAL staff members felt that for some decisions, despite uncertainties, there was enough confidence in the results, while for other results there was a need to further reduce those uncertainties. For other EPAL staff members still, uncertainty was deemed to be too large for results to provide sufficient support to decisions.

For example, quantity and quality water issues in the *Castelo de Bode* dam (primary source of water to the system) due to changes in temperature, precipitation and stream flow were modelled using two sets of emissions scenarios (A2 and B2). This provided information to support decisions on the strategic use of the reservoir relative to other available sources in the future. It also inspired the creation of a protocol with EDP (a large electricity company that utilises the same water source) to agree on rules for the use of water in years of scarcity. However, the reservoir is located in an area prone to forest fires that may require adaptation efforts to prevent such wildfires. Despite the efforts of researchers it was not possible to model the physical interactions of such fire events and their consequences on water quality. Significant uncertainties still remain and no decisions on specific adaptation options were made. This contrasted with the work carried out for the Valada abstraction point (see box on 'dealing with uncertainty') that accounts for about one quarter of EPAL's supplied water. In this case the confidence of EPAL's decision-makers was improved through further analysis to enable them to make decisions on investments in the Water Treatment Plant associated with the abstraction point, such as not to install a nano-filtration system in the near future.

Finally, an adaptation strategy has been prepared, including a diagnosis of EPAL's current and future climate related vulnerabilities, and a set of priotized adaptation options. The strategy was designed to accommodate a general no-regret approach but for some decisions the precautionary principle was applied. The strategy is designed to support decisions on which adaptation options or sequences of adaptation measures (pathways) are better able to cope with the current and future vulnerability. The chosen options are expected to be mainstreamed into EPAL's regular management and strategic planning and can also serve the company in its relationship with external stakeholders. The strategy's implementation is to be monitored by the company and revised every 5 years.

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Links for more information: http://siam.fc.ul.pt/adaptaclima-epal/?lang=en, www.epal.pt

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4.2.2 UK Climate Change Risk Assessment

Country: United Kingdom

Sector:

Scale: National

Organisation: Public

Decision-type: Strategic

Key Messages

The UK Climate Change Risk Assessment (CCRA) was the first-ever comprehensive assessment of the potential risks and opportunities arising as a result of climate change in the UK. The results of the Climate Change Risk Assessment are being used by a variety of government departments in Scotland, Wales and Northern Ireland to facilitate comparisons across sectors, prioritise adaptation actions and improve confidence in decision-making.

Key messages from the CCRA were:

- Despite uncertainties, evidence is now sufficient to identify a range of possible climate change impacts and indicate their relative magnitude to inform adaptation and planning.
- Decision-making needs to consider uncertainties in order to identify robust options.
- Presenting the full spread of results to stakeholders through the use of the "score cards" was a useful way of communicating uncertainty.
- Flexibility needs to be built into adaptation planning to allow for a future climate that may change more slowly, more quickly or in a different way than currently expected.
- The use of "sector champions" appeared to be a useful approach to involve relevant stakeholders in the assessment of risks, including the management of related uncertainties.
- Climate change is only one driver amongst many and should be considered alongside other drivers when assessing future risk.

Background

The UK Climate Change Act 2008 made the UK the first country in the world to have a legally binding, long-term framework to cut carbon emissions and develop adaptation strategies?. As a response to this, the UK government set up the first CCRA, which was reported in 2012 and is scheduled to be updated every 5 years to take into account new data and improved understanding of the issues. This first report outlined some of the most important risks and opportunities presented by climate change across 11 sectors. By analysing existing data, impacts were assessed for three time slices and across three emission scenarios.

The consortium[2] carrying out the review was supported by leading technical experts in the 11 sectors who acted as "sector champions". The aim was to build a consistent picture of risk across the UK and allow for some comparison between disparate risks

[2] HR Wallingford led a consortium consisting of the Met Office, AMEC Environment & Infrastructure UK Ltd, Collingwood Environmental Planning, Alexander Ballard Ltd, Paul Watkiss Associates and Metroeconomica, in order to carry out the review. Sector champions included Cranfield University, CEFAS, Forestry Research, Birmingham University, Acclimatise, the Hutton Institute and the Centre for Ecology and Hydrology.

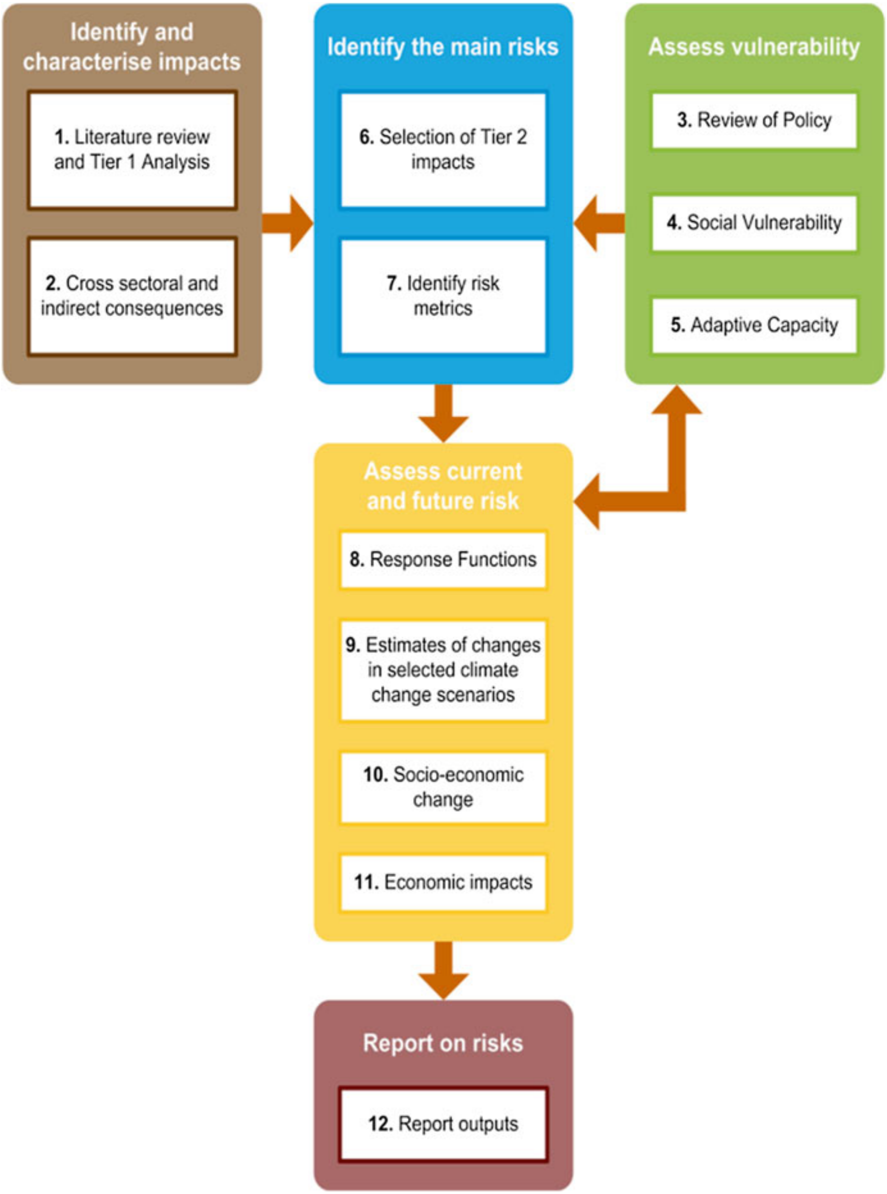

Fig. 4.6 Steps involved in producing the CCRA

and regional/national differences. The UK government was the primary ‘customer’ for the CCRA although the assessment engaged more than 1,800 stakeholders through workshops, online questionnaires and report reviews. These stakeholders came from a wide variety of backgrounds, including non-governmental organisations, leading businesses within sectors, regulatory bodies and government agencies and were involved in identifying and prioritising risks. They also reviewed draft outputs to ensure that the information presented was both understandable and useful.

Process

The steps involved in producing the assessment are described in Fig. 4.6.

Over 700 impacts of climate change were identified (Tier 1) across the 11 sectors under review. These were combined with an assessment of vulnerability across the UK as a whole to identify the main risks. As part of this, a 2nd tier of about 100 impacts was extracted using a simple multi-criteria scoring system based on the magnitude of consequences, likelihood of occurrence and urgency of decision required.

For each impact in the Tier 2 list, one or more risk metric(s) was identified. These provided measures of the consequences of climate change, relative to specific climate variables.

Examples of risk metrics linked to the impact "major drought"

- Reduced summer river flow
- Change in public water supply availability
- Population in areas with future water supply deficits

The next step was to develop response functions, being the relationship between a risk metric (e.g. crop yield) and one or more climate variables (e.g. temperature or precipitation). Response functions were derived in a number of ways:

- Sensitivity analysis of detailed models,
- Historical data to produce a simple statistical relationship,
- Expert elicitation where models or data was not available.

Climate data used

- UKCP09/UKCIP02 projections
- Met Office observed weather and climate
- Hadley Centre HadCM3 (sea ice)
- Low to high emission scenarios
- UKCP09 probability levels

Uncertainties associated with these approaches were taken into consideration as part of the overall confidence scoring for each risk metric. The magnitude of climate risks were then analysed using climate projections for three time slices and three emissions scenarios:

- 2020s (2010–2039) – medium emissions scenario,
- 2050s (2040–2069) – low, medium and high emissions scenario,
- 2080s (2070–2099) – low, medium and high emissions scenario.

It was recognised that many of the risk metrics in the CCRA were influenced by a wide range of drivers other than climate change. For example, risks related to flooding, water supply and demand, health and energy demand were particularly sensitive to future population and a standard set of population projections were applied to across all sectors.

Uncertainty Assessment

Uncertainties were considered in the following areas:

- **Climate system**: driven by limitations in our ability to model certain aspects of the climate system, as well as intrinsic modelling uncertainty and the nature of the system.
- **Future emissions**: captured within the UKCP09 projections that were used in the CCRA to project the risk moving into the future.
- **Current level of risk faced**: particularly important in relation to extreme events, the estimation of which was also subject to considerable uncertainty.
- **The relationship of the risks to climate variables**: through models, statistical relationships and the use of simple 'response function' relationships.
- **Planned or autonomous adaptation and changes in society** (social and economic): assumptions were made on a case by case basis. Population projections were applied but the vast majority of the work in the CCRA took this as a qualitative consideration.
- **Financial consequences** of impacts could only be estimated as part of a monetisation exercise, for example the intrinsic value of elements of the natural environment was not captured.

These uncertainties were handled, amongst others, in the following ways:

- **Emission scenario analysis.** Within each projection a probabilistic range was used, from the 10th percentile to the 90th percentile probability level. Population projections (low, principle and high) were also applied to provide results combining both climate and population changes.
- **Expert elicitation** and **peer-review** were utilised to substantiate whether the assumptions adopted were reasonable.
- **Stakeholder involvement** was utilised to ensure that uncertainties presented in reports were understandable to the reader.

One key method of presenting results to stakeholders, to generate an appreciation of uncertainty, was through the use of "score cards". The risk metrics considered in this first CCRA varied in character and whilst some were quantified, others had to rely on expert elicitation, or a narrative based on the literature. To allow comparison of these different risks, they were categorised as having either 'high', 'medium' or 'low' magnitude consequences and either a 'high', 'medium' or 'low' confidence. An example for agriculture and forestry is shown in Fig. 4.7. This shows the lower (l), central (c) and upper (u) estimates of magnitude of the consequences (based on the range of emissions scenarios analysed and associated probability levels) for the three time slices considered (i.e. the 2020s, 2050s and 2080s) and the overall level of confidence in these estimates (L – Low, M – Medium or H – High).

Metric code	Potential risks for agriculture and forestry	Confidence	Summary Class								
			2020s			2050s			2080s		
			l	c	u	l	c	u	l	c	u
AG1b	Changes in wheat yield (due to warmer conditions)	M	1	2	2	2	2	3	2	3	3
AG9	Opportunities to grow new crops	H	1	1	1	2	2	2	3	3	3
AG1a	Changes in sugar beet yield (due to warmer conditions)	M	1	1	2	1	2	3	2	3	3
AG10	Changes in grassland productivity	M	1	1	1	1	2	2	1	2	2
FO4b	Increase of potential yield of Sitka spruce in Scotland	M	1	1	1	1	1	1	3	3	3
AG1c	Changes in potato yield (due to combined climate effects and CO_2)	L	1	1	2	1	1	2	1	1	2
FO1a	Forest extent affected by red band needle blight	M	1	2	3	2	3	3	2	3	3
AG11	Increased soil erosion due to heavy rainfall	L	1	2	2	1	2	3	1	3	3
AG5	Increases in water demand for irrigation of crops	M	1	2	3	1	2	3	2	2	3
AG4	Drier soils (due to warmer and drier summer conditions)	M	1	2	2	1	2	3	1	2	3
AG2a	Flood risk to high quality agricultural land	H	1	1	2	1	2	2	2	3	3
FO4a	Decline in potential yield of beech trees in England	M	1	1	1	2	2	2	3	3	3
BD12	Wildfires due to warmer and drier conditions	M	1	1	2	1	2	3	2	2	3
FL14a	Agricultural land lost due to coastal erosion	H	1	1	1	1	2	2	2	2	3
WA8a	Number of unsustainable water abstractions (agriculture)	M	1	1	2	1	2	2	2	2	2
FO1b	Forest extent affected by green spruce aphid	M	1	1	2	1	2	2	1	2	3
FO2	Loss of forest productivity due to drought	M	1	1	2	1	1	2	1	2	3
AG8b	Dairy livestock deaths due to heat stress	L	1	1	2	1	1	2	1	1	2
AG7b	Reduction in dairy herd fertility due to heat stress	L	1	1	2	1	1	2	1	1	2
AG8a	Increased duration of heat stress in dairy cows	H	1	1	1	1	1	2	1	1	2
AG7a	Reduction in milk production due to heat stress	L	1	1	1	1	1	1	1	1	3
AG3	Risk of crop pests and diseases	L	Too uncertain								

M	Confidence assessment from low to high
3	High consequences (positive)
2	Medium consequences (positive)
1	Low consequences (positive)
1	Low consequences (negative)
2	Medium consequences (negative)
3	High consequences (negative)
~	No data

Fig. 4.7 Score card indicating the consequences and confidence levels of risk metrics under climate change in the agricultural and forestry sector

For example, metric AG1b "Changes in wheat yield (due to warmer conditions)" is projected (with medium confidence) to have low to medium positive consequences by the 2020s and medium to high positive consequences by the 2050s and 2080s. This can be compared with metric AG10 "Changes in grassland productivity", where it is projected (with medium confidence) to have low positive consequences by the 2020s and low to medium positive consequences by the 2050s and 2080s. Therefore, the score card shows not only shows the scale of the consequences (i.e. low, medium or high), but also the range in uncertainty of the projections (from l – lower, to c – central and u – upper projections) and the speed of onset of consequences (i.e. by the 2020s, 2050s or 2080s). It has been deliberately chosen to use the same colour for both the low positive and low negative consequences. The score card helps the decision-makers to prioritise areas of action by comparing the relative magnitude of risks and indicating how soon action should be taken to mitigate or adapt to that risk.

Fig. 4.8 The M1 and River Trent valley on 10 November 2000 (Source: Frameworks for delivering regular assessments of the risks and opportunities from climate change: An independent review of the first UK Climate Change Risk Assessment. Final Report, 18 June 2012 Robert L. Wilby)

Effect of Uncertainty on Decision–Making

"There is a risk of being locked into maladaptation"

The reports produced from the CCRA reflected potential risks and opportunities and did not purport to be a prediction of the future consequences of climate change. Despite uncertainties over the magnitude and timing of climate change impacts, the CCRA was able to provide sufficient evidence to identify a range of possible outcomes that can inform adaptation policies and planning.

The results are being used by UK government departments and devolved governments as part of their evidence base to support decision-making on adaptation to climate change in organisations across the country. Decision-makers recognise that they need to consider uncertainties and to allow flexibility in their policies and plans, and they need to report their actions under the "Adaptation Reporting Power" of the Climate Change Act 2008. Decisions range from the simple "low cost, no regret" measures, such as urban greening, through to the adaptation pathway approach, in which flexibility is maintained and adjustments made if conditions or information change. An example of the latter is the Thames Estuary 2100 project being a multi-million pound contract planning for flood risks in London. The CCRA provides a probabilistic climate change framework with differing degrees of confidence over various outcomes to facilitate this decision-making process (Fig. 4.8).

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Links for more information: http://www.defra.gov.uk/environment/climate/government/risk-assessment/

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4.2.3 Water Resources Management in England and Wales

Country: United Kingdom
Sector:
Scale: Local
Organisation: Public
Decision-type: Strategic

Key Messages

"The effects of climate change uncertainties are not as immediate as issues such as changing water demand"

This project stemmed from the desire of the Environment Agency of England and Wales to account for the large uncertainties in climate change projections in planning water requirements of the future.

Key messages from this work were:

- Planning based on just a few storylines was a risk in itself.
- There was a need for water management options that are flexible and robust under a range of possible futures.
- Tools, such as large climate model ensembles in combination with risk based decision-making frameworks, can be used to avoid poor adaptation decisions.

Background

This research project was commissioned by the Environment Agency of England and Wales and initially carried out by the School of Geography and the Environment, Oxford University. Every 5 years, water companies have to indicate how they will guarantee the supply of water over the following 25 years. The Environment Agency wanted to provide guidelines to water companies on how to take into account large uncertainties in climate change information when preparing the associated 5 year Water Resources plans.

Water companies in England and Wales have considered the impact of climate change in their plans since 1998, but approaches tend to be simple and deterministic, as climate change is one of many factors that companies have to take into account. The Environment Agency wanted to explore how large ensembles of climate information could be used to improve decision-making.

Apart from the Environment Agency, other stakeholders included managers from some of the water companies, climate scientists, and hydrologists. All of these were consulted during the development of the project.

Process

"Tools need to be simple and cheap"

The project concentrated on exploring climate model related uncertainties as represented by the climate data described on the box.

Climate data used

- Perturbed physics ensemble (PPE) – 247 members – based on the HADCM3 model
- An ensemble of opportunity consisting of 21 General Circulation Models (GCMs) available through the CMIP3 database (IPCC [4th] Assessment Report)

Both ensembles were run under the SRES A1B emissions scenario.

It was the first project to use such a large range of climate models to study the effects of climate projection uncertainties on the management of a water resources system. The Environment Agency was involved in the design of the project, the selection of hydrological modelling tools and calibration of models, and the choice of adaptation options. Workshops were also organised so that the scientists could understand the information needs of decision-makers in this sector, and determine the sort of information that could be provided.

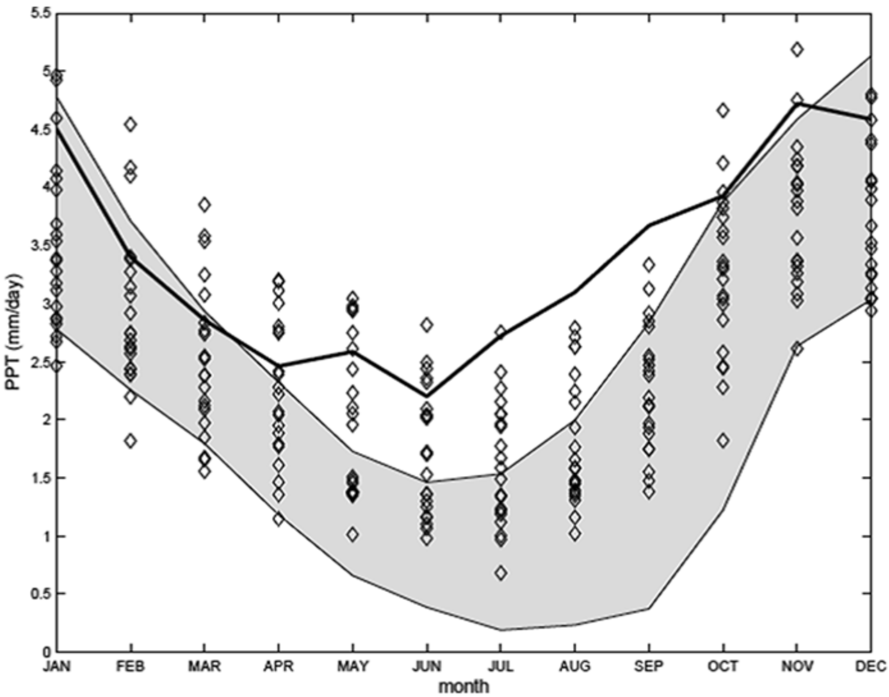

Fig. 4.9 Mean monthly precipitation (mm/day) for 1930–1984. The thick line corresponds to observed monthly means, the grey shadow indicates the range of precipitation simulated by the PPE, and the diamonds indicate the CMIP3 models results

The large ensemble of climate projections was run through a hydrological model and then a water resources model for a catchment in the South West of England, to evaluate the time dependent risk of failure to supply water demand under different adaptation options. The hydrological and water resource models were already in use by water supply companies and regulators. Since time and expense was not required to develop these tools it was hoped that they would encourage the take up of information from large ensembles of climate models.

An example of the exploration of uncertainties in climate projections can be seen in Fig. 4.9 which shows the mean monthly precipitation (mm/day) for the period 1930–1984. The fact that, in this case, uncertainties in the ranges of model physics (PPE) and model structure (CMIP3 models) do not coincide, shows that both ensembles are necessary to better explore the full range of climate model uncertainty.

Uncertainty Assessment

The primary uncertainties analysed by running the large ensemble of climate models through the water resources system model were those due to:

- climate model structure represented by the CMIP3 models,[3]
- climate model physics represented by the perturbed physics ensemble (PPE).[4]

Other sources of uncertainty such as emission scenario and impact model uncertainty were ignored in this study. It is expected that the uncertainty range might vary when all sources are taken into account.

Within the Environment Agency there was already an awareness of uncertainties in climate change risks. They became particularly interested, however, in the fact that the range of uncertainties explored by the PPE was in general larger than that expected from the CMIP3 ensemble.

Water companies find large ensembles of climate information difficult to use. As a result of this and other projects, guidance was developed in two areas:

- Translation of climate ensembles into a range of river flows being a format that is familiar to water companies. This effectively gave them a set of impact data to use.
- Guidance on how to use the data. This gives them the confidence that using the approach will result in robust decisions.

Water company representatives argued that even though they found the results interesting, they did not have the resources to implement such analysis. They also commented that climate change risks represent only a small part of the total risks they have to face. For instance, in many parts of the UK, the main problem is changes in demand due to population increase. Even though plans have to be made for 25 years into the future, climate change and climate risks may not be the most significant risk drivers. Consequently, water companies preferred the simplified idea of using a maximum of three climate scenarios (low, medium, high) to explore climate change impacts.

[3] http://www-pcmdi.llnl.gov/ipcc/about_ipcc.php

[4] http://climateprediction.net/

Example of handling uncertainty: failure of water supply

This represents the case of a water company required to meet water demand in its catchment region into the twenty-first century at a minimum cost. The top panel of Fig. 4.10 shows a histogram of the percentage change in summer average precipitation of 2050–2079 compared to 1960–1989, for the PPE ensemble.

The bottom panel of Fig. 4.10 shows, for each range of precipitation change on the top panel, the corresponding average number of failures to supply the required demand for the business as usual (BAU) scenario and four different adaptation options. The adaptation options available include increase supply (green and purple lines in bottom panel) and/or reduce demand (red and light blue lines in bottom panel). The blue line represents business as usual. Robust adaptation options are those that, for an acceptable level of risk, reduce the risk of failure across a range of plausible climates. If for instance only five failures are acceptable, only red, light blue and purple adaptation options are robust across the range of plausible futures.

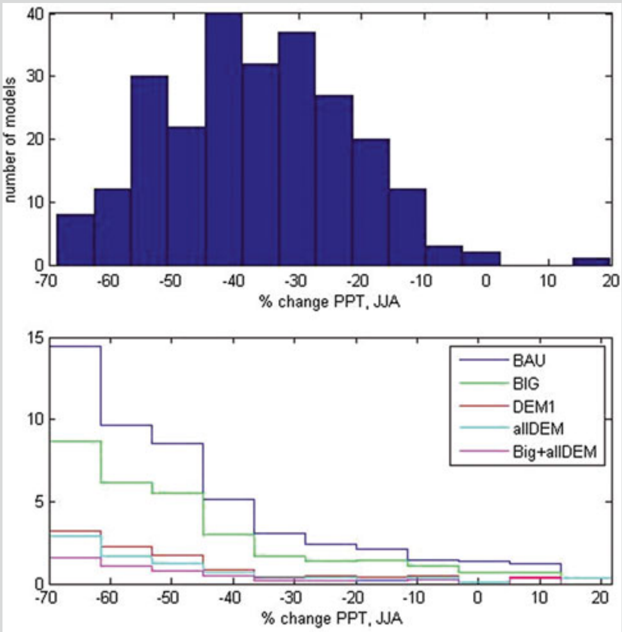

Fig. 4.10 Histogram of the percentage change in summer average precipitation of 2050–2079 compared to 1960–1989, for the PPE ensemble (*top panel*); Average number of failures to supply the required demand for the business as usual (BAU) scenario and four different adaptation options

Effect of Uncertainty on Decision–Making

"Planning based on just a few storylines is a risk in itself"

This exercise showed that using information from a small number of projections could be misleading, either over or underestimating the changes in climate risks. The Environment Agency and water companies accept that planning based on just a few storylines is a risk in itself.

From the water companies' perspective, there are many existing uncertainties other than climate change which tends to be a long-term issue. Uncertainties due to demand and environmental standards for example are much more relevant on a short-term basis. However, they appreciate the need for the use of many models and are willing to utilise the results as long as it is relatively simple to do so.

From the results produced, the Environment Agency has developed guidance on the use of probabilistic climate change information to explore sensitivity and minimise surprises for the next round of water resources plans. This will be used for the plans due to be drawn up in 2014. It will be interesting to see whether the attitude of the water companies changes after this round of plans.

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Links for more information: Information about the Environment Agency guidelines for managing drought and the balance between water supply and demand can be found at http://www.environment-agency.gov.uk/business/sectors/32399.aspx

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4.2.4 Water Supply in Hungary

Country: Hungary

Sector: 

Scale: Regional

Organisation: Public

Decision-type: Operational+Strategic

Key Messages

This project investigated the effects of climate change on drinking water supply in two regions of Hungary in order to support decisions on adaptation.

Key messages from the project were:

- Despite uncertainty in long-term trends of precipitation and the hydrological consequences, decisions were found to be possible.

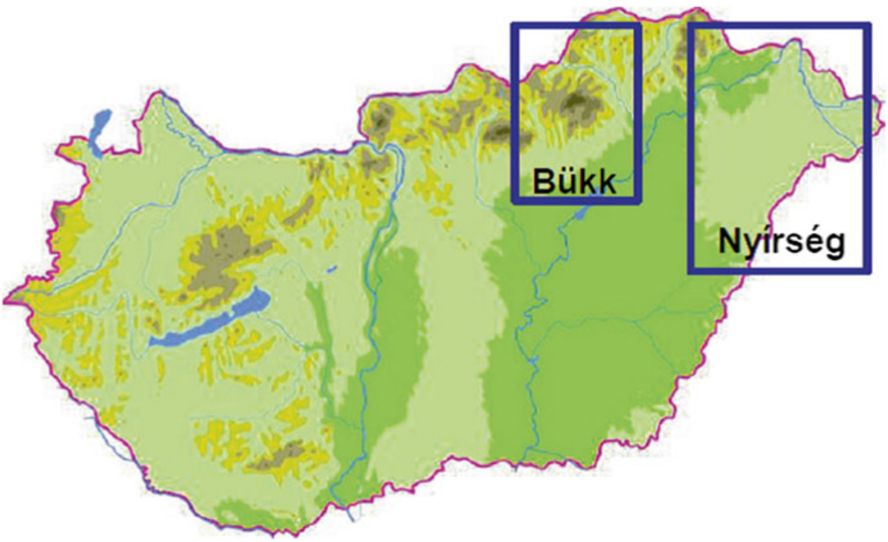

Fig. 4.11 Hungarian test areas

- As a preparation for adaptation planning, all current and future hazards should be estimated and ranked according to likelihood and severity of consequences as in the Water Safety Plan of the World Health Organization.

Background

The Hungarian National Institute for Environment (NeKI) is responsible for the water management policy of Hungary and acted as partner in the Climate Change and Impacts on Water Supply (CC-WaterS) project. The aim was to assess the climate change impacts on the future availability and safety of public water supply. In order to provide information to water managers, it considered the economic losses or benefits related to changes in climate and land use. The project was funded under the South East Europe Transnational Cooperation Programme, comprising 18 partners and was completed in May 2012.

Two specific areas located in the north-eastern part of the Hungary were analysed: the mountainous Bükk region, and the plain area of Nyírség (see Fig. 4.11). The Bükk-Mountain region encompasses the highest karstic plateau of Hungary, situated in the Carpathian Mountains. From the group of karstic springs in its South Eastern section, one large city and three villages (about 190,000 people) are supplied by one water company. The lowland area of Nyírség is part of the Great Hungarian Plains and located near the Tisza River. The mean elevation of this region ranges between 150 and 200 m. and about 260,000 people live here, settled in one large city and 60 smaller settlements. The drinking water is obtained from shallow and deep porous aquifers of the alluvial deposit and supplied by one large regional water company (84 % of the

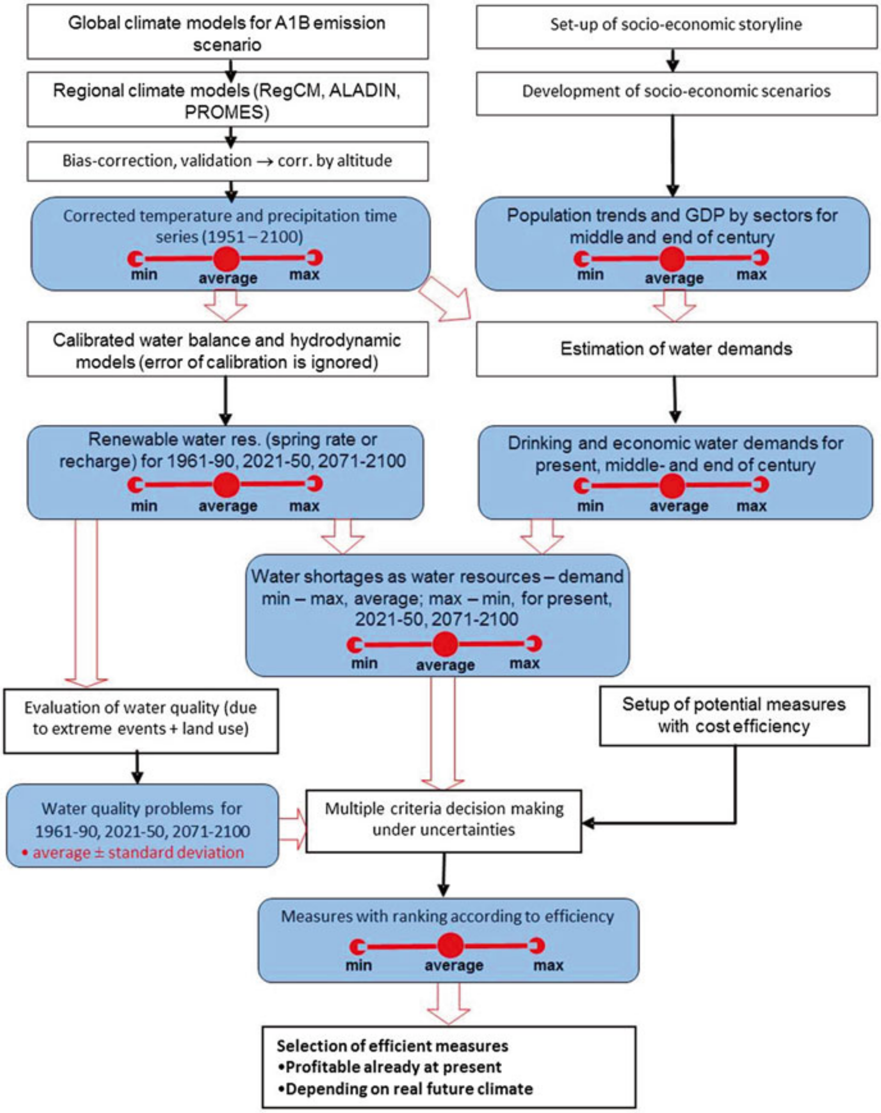

Fig. 4.12 Process of the assessment, including uncertainties (in *red colour*)

population) and a number of small waterworks. The two large water companies, representative of each region, were involved from an early stage in the study.

The main phases of the project, including the uncertainties involved are summarised in Fig. 4.12. This shows the relationships between different steps such as the establishment of climate datasets, the determination of water resources availability, estimation of water demands, evaluation of problems and selection of efficient measures, and the consideration of uncertainties (in red colour).

The project utilised three regional climate models (RCMs) and the SRES A1B emission scenario, with appropriate corrections (see box). To project the impact of climate change on drinking water availability and quality, the precipitation and temperature time series from the RCMs were used as input for a water balance model, a hydrodynamical model and a crop model. These models also took land use changes due to climate change into account.

Climate data sources

- SRES A1B emission scenario and three RCMs (ALADIN; RegCM and PROMES) were selected for modelling time series of temperature, precipitation and CO_2 concentration up to 2100
- The time series were bias corrected for the two pilot areas using temperature and precipitation data of E-OBS database (1961–90 period).
- Climate data was validated using observations other than those in E-OBS database. In the Bükk region correction according altitude was necessary.

Without a particular link to possible climatic futures, local experts were asked to develop a storyline showing their perceptions of the future for all social and economic aspects such as: market policy, declining and growing sectors, technical development, unemployment, governance structure, role of policy, demography, sustainability and equity. Project managers then used the storyline to develop three scenarios indicating a maximum, minimum and plausible future water demand. Experts and the two water companies were asked to provide feedback on the scenarios.

The changes in the drinking water demand were estimated on the basis of the three socio-economic and regional climate scenarios (maximum, minimum and plausible).

In the last project phase, cost-efficient adaptation measures were selected.

Uncertainty Assessment

All the stakeholders recognised uncertainties, and none of them considered them to be barriers to adaptation. Experience of very heavy precipitation in Bükk (in 2006, 2009 and 2010) and drought in both regions (beginning of 90s, 2000, 2003, and 2007) had convinced them that climate change is an issue which needs to be considered. Water management companies are not worried *whether* climate change will occur but *what* are the possible scenarios and the corresponding efficient measures.

Uncertainties of the following applied models and methods were dealt with:

- Regional Climate Models,
- Hydrological/ hydrodynamical impact models,

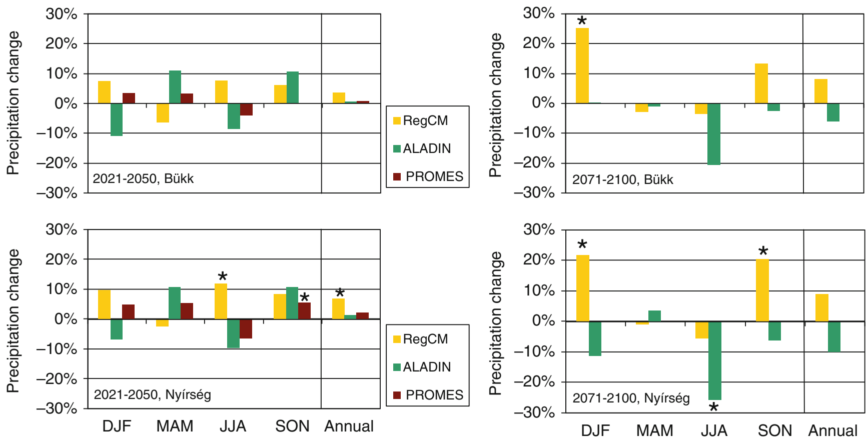

Fig. 4.13 Projected changes in seasonal mean precipitation with the use of three regional climate models, for 2021–2050 and 2071–2100. Significant changes (at 0.05 level) are indicated by asterisks (CC-WaterS, 2010 http://www.neki.gov.hu/uploads/458/Attachments/cc_waters_wp3.pdf)

- Empirical methods for estimating water balance elements (e.g. evapotranspiration),
- Land use change evaluation methods,
- Crop models for evaluation of nutrient balance elements and yields,
- Evaluation methods for socio-economic changes.

A combination of the following methods was used to address uncertainties:

- Expert elicitation,
- Sensitivity analysis of parameters, comparative analysis of formulas,
- Probabilistic multi model ensemble,
- Fuzzy Multiple Criteria Decision Making (see box).

When the project began it was expected that the results given by the three RCMs would be more or less similar but the models presented different climate changes. As can be seen in Fig. 4.13, simulations of the RCMs often do not agree even on whether the projected changes in precipitation is positive or negative. Uncertainty related to predicted seasonal precipitation with different RCMs is larger than the changes compared to the baseline. The uncertainty was more pronounced in precipitation than temperature (not shown), which shows clear and continuous increase in all seasons.

In addition, short heavy rain (causing quality problems in Bükk recently) could not be modelled which poses difficulties in planning adaptation measures against flash flood events.

Evapotranspiration seems to be the most uncertain water balance element since the parameters of the empirical formulas are perhaps not valid under considerably higher temperature. The most realistic formula was selected based on comparative analysis.

In order to draw conclusions on water availability, it was important to determine the uncertainty of climate data in water balance and hydrodynamical modelling, carrying out several simulations with various climate data. As a result, the uncertainty of the available water resources was presented as a range of possible values alongside the average values. It was noted that uncertainties in the parameters of the water balance model and hydrodynamic model were reduced through a detailed calibration procedure.

To analyse future water demand, population birth/death ratio and migration rates were projected, given envisaged economic conditions, social measures, employment and income. The impact of climate change was also considered on the likely increase in water demand for hygienic use and for watering gardens, in proportion to the increase of temperature. In this way, uncertainty in the meteorological prognosis was also incorporated in the estimation of water demand.

In the last step of the process, a Fuzzy Multiple Criteria Decision Making tool was applied to help the water companies take decisions. The best adaptation option can be selected when multiple alternatives exist even under uncertainty, represented by so called fuzzy numbers (see box).

Handling uncertainty – Fuzzy Multiple Criteria Decision Making

Fuzzy sets (representing the minimum, maximum and average values of a parameter) were used to estimate ranking criteria values e.g. cost, acceptance, flexibility and lag time and then to evaluate the composite indicator numbers. Fuzzy Decimaker version 2.0 was used as a Fuzzy Multiple Criteria Decision Making tool that helps the user to select the best solution considering a number of conflicting criteria under uncertainties.

Effect of Uncertainty on Decision-Making

Despite the fact that each of the three regional climate models gave different results, water management companies were prepared to accept the uncertainty and act. They proposed that different adaptation measures should be developed for the future range of scenarios (maximum, minimum and average). Several alternative management measures were formulated: water supply management, water demand management, shortage consequence management, change of allocation of available supply among users, water quality management and combinations of the alternatives. In the mountainous area the water management company has established a new system to monitor heavy rains and flash floods. It also intends to install a new treatment plant which can be used to protect water quality during flash floods. A proper monitoring system to measure climate and hydrological parameters was considered essential for dealing with uncertainty.

In the low lying area the regional company has begun to shut down very small water works and is trying to concentrate on larger water sources, developing a regional pipeline system in order to increase the safety of water quality. They have also made a study of prospective refuges into which they can move their operations which would make the water system less vulnerable to extreme events.

Author: Agnes Tahy and Zoltan Simonffy

Links to more information: http://www.ccwaters.eu, http://www.neki.gov.hu/?TeruletKod=0&Tipus=content&ProgramElemID=66&ItemID=458

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4.2.5 Climate Change *and Health in The Netherlands*

Country: Netherlands
Sector:
Scale: National
Organisation: Public
Decision-type: Strategic

Key Messages

This case study assessed the degree of uncertainty in various potential health effects of climate change in the Netherlands.

Key lessons learned were that:

- Potential health effects due to climate change were associated with large uncertainties and knowledge gaps.
- Analysing and characterising uncertainty by means of a typology combining a scale of 'Level of precision' with 'Relevance for policy' was very useful for the selection and prioritisation of robust adaptation policies.
- Recognition of uncertainty of various health effects due to climate change had implications for policy. For example, adaptation policies that focus on enhancing the health system's capability of dealing with uncertainties were most appropriate for climate related health impacts characterised by recognised ignorance.

Background

Climate change can influence public health in many, often subtle and complex ways. Some of these potential impacts are direct, such as the impact of heat waves on heat-related deaths. Others are more indirect, such as the effect of changing climates on the distribution of vectors such as specific types of mosquitoes, which affect the

Fig. 4.14 A warning of cyanobacteria for swimmers

Fig. 4.15 The oak processionary caterpillar which entered the south of the Netherlands in the 1990s and gradually spread north. A further spread and increase in population size is expected due to climate change

distribution and risk of disease outbreaks (Figs. 4.14 and 4.15). There is a colourful mix of information on the topic, ranging from qualitative discussions on plausible impacts, through lists of knowledge gaps and research needs, to detailed quantitative studies. Projections of health risks of climate change are surrounded by uncertainties, leading to difficulties in determining the policy approach.

The Netherlands Environmental Assessment Agency (PBL), being the Dutch national institute for strategic policy analysis in the field of the environment, nature and spatial planning, has recently produced the assessments "Impacts of climate change in the Netherlands: 2012" (2012) and "Roadmap to a climate-proof Netherlands" (2009) for the Dutch government. Within these assessments it was important to account for uncertainties in a policy-relevant way and so PBL asked Utrecht University to characterise the uncertainties associated with various health effects, and to provide strategic options on how to deal with them in adaptation policy.

Process

The process carried out by the Utrecht University was as follows:

- A list of 33 potential health impacts of climate change was compiled based on existing Dutch impact assessments and international literature. These impacts were grouped into eight health themes: temperature, allergies, pests, vector-borne diseases, food/water-borne diseases, air quality, flooding/storm and UV effects.
- A questionnaire based on expert elicitation was completed. National and international experts (scientists and practitioners) were asked to indicate the level of precision with which health risks could be estimated given the present state of knowledge.
- Suggestions were made for dealing with uncertainties in climate change adaptation policy strategies.

Categories of health impacts of climate change included

- Temperature
- Allergies
- Pests
- Vector-borne diseases
- Food- and waterborne diseases
- Air quality
- Flooding and storm
- UV-related

The results of the study were used as input to PBL's impact and adaptation assessment. They were also presented at a World Health Organization (WHO) workshop on policy options for climate change and health.

Uncertainty Assessment

In the first part of the study the participating experts were asked questions to assess the 'Level of Precision' with which health risk estimates could be made given the current state of knowledge. They were also asked to provide full backup for their scores. For example:

- Why is it possible to indicate the direction of change, but not provide a quantitative risk estimate?
- What factors prevent a more precise analysis (e.g. whether data is unavailable, or cause-effect relationships not understood)?
- What factors are available that allows a certain level of precision to be applied (e.g. whether well-established models or detailed data sets are available)?

Example of handling uncertainty: 'Level of Precision' scale

The following 'Level of Precision' scale was used to assess the degree to which health effects of climate change can be quantified:

1. Effective ignorance
2. Ambiguous sign or trend
3. Expected sign or trend
4. Order of magnitude
5. Bounds
6. Full probability density function (i.e. full quantitative risk assessment possible)

The scale provides a range from a qualitative indication i.e. whether it is good or bad for health, a rough estimate of the order of magnitude (i.e. 'hundreds of cases' of disease versus 'thousands of cases'), or a detailed risk-based assessment.

The questions covered the following categories of uncertainties:

- The climate system, e.g. heat wave frequencies and durations.
- The biological systems, e.g. the relationship between climate and insect distributions, and infection biology.
- The human systems, e.g. autonomous adaptation and responses of health systems, effectiveness of hygiene regulations, and disaster response.

The uncertainty typology or the 'Level of Precision' scale used is shown in the box 'Example of handling uncertainty'. The 'Level of Precision' question was relatively broad. Potentially, some participants could have scored health effects based on standard climate projections (e.g. the Dutch KNMI or global IPCC scenarios), while others could have assumed a broader ignorance regarding local climatic changes. Because the reasoning focused almost exclusively on uncertainties in assessing health impacts (i.e. translating a climatic change into its health impacts),

Health effects have:	Low policy-relevance	High policy-relevance
High level of precision health risk assessment	Tailored, prediction-based strategies (e.g. risk approach) Focus: low costs/efforts or co-benefits. **Example:** providing shelter for homeless people during cold spells.	Tailored, prediction-based strategies (e.g. risk approach) Consider (but critically reflect on) costly and extensive options. **Example:** financing/subsidizing air-conditioning or other (advanced) cooling systems in buildings.
Low level of precision health risk assessment	Enhance system's capability of dealing with changes, uncertainties, and surprises (e.g. resilience approach). Focus: low costs/efforts or co-benefits. **Example:** general improvement in health care including research, and regular impact & adaptation assessments.	Enhance system's capability of dealing with changes, uncertainties, and surprises (e.g. resilience approach). Consider (but critically reflect on) costly and extensive options, including precautionary options. Assess overinvestment risks and flexibility. Under which circumstances would "robust" measures be advocated and which? **Example:** changing building materials and increasing urban water and parks to reduce the impact of heat in urban areas.

Fig. 4.16 Appropriate adaptation approaches, considering uncertainty and policy-relevance of health effects (Wardekker et al. 2012)

rather than on climatic uncertainties, the scores were interpreted as 'given a climate scenario'. The individual scores, the expertise-weighted descriptive statistics, and the reasoning given for each score were assessed.

The second part of the study dealt with:

- The relevance of health effects to adaptation policy (e.g. where there are high health impacts, high societal or political salience, etc.),
- Specific uncertainties not mentioned in the reasons given for the 'Level of Precision' scores, and
- Uncertainty-robust adaptation options and strategies.

The relevance of health effects to adaptation policy was assessed by asking participants to select and rank the five effects they considered the most important, interpreting relevance in a broad way, and giving reasons for their choices. This separated the highly relevant from the less relevant effects, and highlighted the different reasons for relevance. For example: current vulnerability to the effect (heat-related mortality); large potential health and societal impacts, difficult to adapt to, and public fright factors (vector-borne diseases); and a large number of people affected and large potential economic impact (hay fever).

The implications of uncertainties for adaptation were discussed using various characteristics of policy options (e.g. costs, flexibility, encroachment, prediction versus capacity-enhancement). The results of this approach are summarised in Fig. 4.16.

Effect of Uncertainty on Decision–Making

"The uncertainty typology can be a very useful assessment tool for the selection and prioritisation of preferred climate adaptation policy in practice."

The uncertainties assessed had a notable influence on the policy assessments conducted by the PBL for the Dutch government; it affected how they discussed climate change impacts on health and adaptation to these impacts. It became clear that adaptation in the health sector requires a strong focus on enhancing system resilience and on capacity building. The use of uncertainty typologies was also important; they allowed for a systematic and structured analysis of the uncertainties, distilling policy-relevant uncertainty information from the complex mix of imperfect evidence. They have led to the advice that a different policy approach would be needed, for example, for vector-borne diseases than for heat-related deaths. In effect they have made the various potential health impacts and their uncertainties comparable, which in turn have enabled adaptation strategies to be differentiated.

The typologies helped to focus on the most appropriate policy strategies, given the characteristics of both health impacts and policy options:

- For possible climate related health impacts characterised by ignorance, the most appropriate adaptation policies are those that focus on enhancing the capability of the health system and society in general in dealing with possible future changes, uncertainties and surprises e.g. through resilience, flexibility, and adaptive capacity.
- For climate related health effects for which rough risk estimates are available, 'robust decision-making' is recommended.
- For climate related health impacts which are less uncertain, tailored and prediction-based approaches are most appropriate.

By providing an interpretative framework for a complex mix of uncertain evidence, a systematic, rather than ad-hoc, formulation of policy advice is created. An example is the central role that uncertainties and uncertainty-proofing policy played in the workshop "Policy options for climate change and health" (PBL & WHO Europe, co-organised by the University of Utrecht, at the WHO office in Bonn, Germany, 11–12 January 2010). The outcome of this case has also been used in a recent follow-up of the PBL outlook studies on climate-proofing in the Netherlands to support the current national Delta Programme (addressing flood risks, fresh water availability, and urban stress). The developed framework for systematically dealing with uncertainties will be used to advocate a second Delta Programme, including a detailed health adaptation policy.

Authors: Arjan Wardekker, Jeroen van der Sluijs

Links to more information:

Wardekker, J.A., A. de Jong, L. van Bree, W.C. Turkenburg, and J.P. van der Sluijs (2012). Health risks of climate change: An assessment of uncertainties and its implications for adaptation policies. *Environmental Health* 11: 67. http://www.ehjournal.net/content/11/1/67

The paper was summarized in the European Commission newsletter Science for Environment Policy: http://ec.europa.eu/environment/integration/research/newsalert/pdf/317na5.pdf

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4.2.6 Flood Risk in Ireland

Country: Ireland
Sector:
Scale: National
Organisation: Public
Decision-type: Strategic

Key Messages

The aim of this study was to look at how climate change has been integrated into existing policies for flood protection works and how robust those policies are under a range of climate change scenarios.

Key messages were:

- Reinforcement of the emerging picture that there is uncertainty in projections.
- Consideration of the performance of adaptation options over a wide range of uncertainty to ensure the robustness of the decision.
- The importance of communicating uncertainties in future projections so that decisions can be based on the full range of available information.

Background

In recent years flooding in Ireland has been quite extensive with substantial social impact. This case study looked at how climate change has been integrated into existing policies for flood protection works, and how robust those policies are.

The project was initiated by the Department of Geography at the National University of Ireland Maynooth and funded by the Science Foundation Ireland (SFI). The main beneficiary of the project was the Office of Public Works (OPW), the national agency responsible for flood risk reduction, whose policies were selected for review. Their policy reports have been influential in past decisions and they are one of the leading national agencies in Ireland that are climate sensitive and trying to accommodate changes.

Most of the work in flood defence in the past has been based on high resolution regional circulation models (RCMs), with a tendency to neglect other uncertainties such as those arising from the use of different general circulation models (GCMs), downscaling techniques, different socio-economic, emissions and land-use/soil sealing scenarios, and impact models. It is critical, for example to include results from a large sample of GCMs to assess the robustness of adaptation schemes. There is also a risk of overconfidence in projections due to the high resolution of RCMs. In adapting to an uncertain future it is important that more effort is made to capture the full range of uncertainties so that decisions are based on as much information as possible.

Process

The first step was to review the policy documents from the OPW. Identified safety margins incorporating climate change allowances were stress-tested using climate projections extracted for the Irish grid cell and pattern scaled to local catchments.

Climate data sources

- IPCC AR4 full range of GCMs (17 in total)
- Three emissions scenarios
- Time horizons 2020s, 2050s and 2080s

Fifty one climate projections were generated from IPCC AR4 data using the entire range of GCMs and three IPCC emissions scenarios. Change factors based on current climate conditions were determined and run through a weather generator to derive catchment scale information. This was then used to force a suite of hydrological models for four case study catchments. The model structure and parameter uncertainty of the hydrological models were accounted for and the sensitivity of safety margins for flood defences was assessed using risk response surfaces.

The OPW was involved in the study through informal meetings and conferences.

Uncertainty Assessment

The primary aim of the project was to test a set of adaptation options on flood risk for their robustness. This was done using sensitivity analysis on the flood defence thresholds incorporated in the policies. Peak flow safety margins of 20 %, for a medium emissions scenario, and 30 %, for a higher scenario were identified for new design flood defences, so sensitivity analysis was used to check how robust those

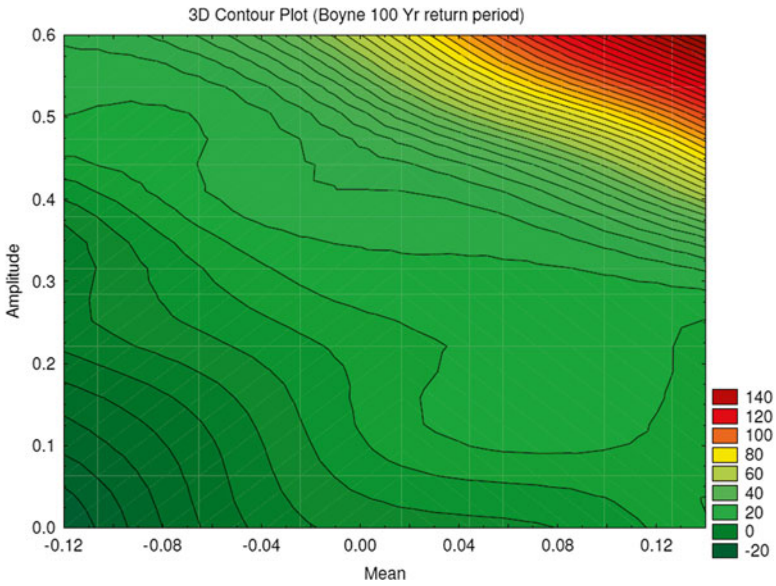

Fig. 4.17 Risk response surface for safety margins of 20 %. Only in case of a combination of relatively high mean precipitation change and high amplitude of precipitation a safety margin of 20 % will not be sufficient for the majority of projected changes in flooding

margins were over as much of the uncertainty range as possible. The research found that the performance of these safety margins differs between catchments. In some instances they were sufficient to cope with the range of scenarios analysed. In others, the safety margins were found to be too conservative for the range of climate projections considered, leaving high residual risk.

The project dealt with the following uncertainties:

- Emission scenarios,
- Global climate models,
- Natural variability,
- Hydrological model – both model structure and parameter uncertainty,
- Potential for future surprises in climatic conditions.

These uncertainties were dealt with in the following ways:

- Sensitivity analyses of which the results are displayed in risk response surfaces
- Risk response surfaces (see Fig. 4.17). These were used to visualise the effectiveness of the policy decision, given certain ranges in temperature and precipitation and the safety margins applied.
- Wild cards

Figure 4.17 displays the results of the sensitivity analysis in a response surface. Future precipitation changes are represented here as the mean and amplitude of the range of precipitation changes. It can be seen that a 20 % safety margin (based on current norms) shown as green area accounts for the majority of projected changes in flooding. However, it is apparent from the yellow and red areas (which exceed the 20 % allowance) that approximately one quarter of all simulations are not catered for by this safety margin. This can be thought of as the amount of residual risk associated with the policy of a 20 % allowance in flood design. The risk response surface was communicated to stakeholders at national meetings and conferences.

Following previous work done by others, particularly in the UK, the expansion of the sensitivity range on both the upper side and lower side to account for new extreme precipitation scenarios was also reviewed.

The project also considered uncertainty in the impacts models, i.e. the simple rainfall runoff models. This was done by looking at different model structures and parameter uncertainty.

Effect of Uncertainty on Decision-Making

"Ensure decisions are robust"

Using 51 different climate scenarios combined with uncertainties in downscaling and hydrological models, meant this was the biggest assessment of uncertainty in hydrological studies so far in Ireland. Previously the OPW has tended to use three scenarios to inform their decisions, but this work has reinforced their growing understanding that uncertainties need to be fully understood in order to take robust decisions. The OPW is moving away from a deterministic approach to adaptation decisions. This revolved around making specific assumptions about the way the climate will change, and designing structural engineering solutions such as building flood defences, perhaps with the capacity to increase their height in the future. They are now approaching decisions with softer techniques to ensure that they are robust under the full range of uncertainties involved.

A good example is Cork City, where a complete structural protection scheme against both fluvial and coastal flooding would have cost in the order of €140 m but would have given a reducing standard of protection over time. This is due to the fact that typical engineering approaches are built to a specific standard. As climate changes, the level of protection offered decreases potentially making the initial outlay of costs unjustified.

The proposed solution is therefore to provide partial defences through the city, with potential amendments to the reservoir operations and some localised protection works upstream of Cork, where land would be deliberately flooded to reduce fluvial flood risk. Barrages are also being considered as suitable alternatives to traditional defences (Fig. 4.18).

Fig. 4.18 Flood problems in Cork (Courtesy: Irish Examiner)

Author: Conor Murphy

Links to more information: Bastola, S., C. Murphy, and J. Sweeney. 2011. The sensitivity of fluvial flood risk in Irish catchments to the range of IPCC AR4 climate change scenarios. *Science of the Total Environment* 409(24): 5403–5415.

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4.2.7 Coastal Flooding and Erosion in South West France

Country: France
Sector: 
Scale: Local
Organisation: Public
Decision-type: Operational

Key Message

This project deals with the increased risk of coastal flooding and erosion through sea-level rise in South West France.

The key message from the project was:

- Using a low/no regret approach serves many functions, such as solving the flood problem, adding value to natural reserves and creating new potential for recreation.
- Add other messages, such as the feasibility of taking meaningful action in the absence of precise predictions of future changes, etc.
- Meaningful coastal investments can be made in the absence of precise predictions of future changes.
- Climate change impacts can be strong drivers to implement projects that strive for both current and future vulnerability.

Background

The lido[5] between Sète and Marseillan in the Languedoc-Roussillon region of France was threatened by sea level rise and erosion. During the last two decades coastal erosion and flooding have caused increasing traffic disruption on the road between the two towns and the inland biodiversity and heritage was additionally impacted by storm surges. Protection was also needed for economic activities such as vineyards and oyster farming in the Thau pond, as well as the sand beach and the local campsite.

The threat triggered a comprehensive spatial planning project run by the Community of Communes. The project was driven by a desire to counter beach erosion and the climate change dimension wasn't initially considered; it was launched in 2000 with a view to targeting soft protection measures rather than concrete devices. Sea level rise was primarily considered during the implementation phase to ensure that the measures taken would be sustainable in the long term.

Funding was provided by the State, the local authorities (regional and departmental) and the European Union through the European Regional Development Fund (ERDF). An Interreg III project has also been conducted for its demonstrative and innovative purposes.

Process

A study into the feasibility of moving the road, and the sustainable land planning of the lido, started in 2003 and was completed in 2005 with many public consultations. The public consultation is a mandatory process in France, required for significant

[5] Public place for beach recreation, including a pool for swimming or water sports.

spatial planning projects in order to identify natural, social and cultural issues. After completion of the consultations, the development project was finalised and the works started in early 2007.

Climate data used

Ministry of Environment recommendation on sea level rise for long-term planning to be + 25 cm by 2050 (DGEC/ONERC 2010).

The current vulnerability to flooding was well known, but data from the Ministry of Environment recommended considering a sea level rise of over 25 cm by 2050. The Community considered the option of leaving the road as it was, but the cost-benefit analysis delivered many benefits of a strategic relocation of the road behind the lido. One of these benefits was the fact that such a move, combined with a regeneration of the sand dunes would "climate-proof" the area against potential flooding for over 50 years. The new road became operational during summer 2010 and the rehabilitation of the sand dunes of the lido continued until 2011 (Figs. 4.19–4.21).

Fig. 4.19 Recurrent erosion impacts on the coastal road

Fig. 4.20 Global overview before the commencement of the project showing the road situated next to the beach

Fig. 4.21 Global overview after completion of the project showing the road moved inland and the restoration of a wider beach and sand dune

Uncertainty Assessment

The two main types of uncertainty were:

- The exact value of sea level rise and its associated extreme wave heights from storm surges.
- Erosion trends under sea level rise.

To cope with the uncertainty surrounding the magnitude of sea level rise, the project decided to combine the relocation of the road with protection of the sand ridge and restoration of the beach width. Expert advice from the technical advising contractor was taken and there was public consultation with stakeholders. The road was moved behind the lido and the sand dunes restored to a height of 4.2 m above sea level. The new road relocated inland has been raised by 1.5 m in order to reduce the risk of permanent road flooding during strong storm surges and to anticipate the new flood risk management scheme; the regional Disaster Risk Management unit has strongly supported the idea of raising the road.

In addition, the restored dunes were populated with plants stored prior to the start of the project and the position of the dunes is now being monitored with cameras along the beach line. Some innovative coastal defense measures are being taken (e.g. sunken geotubes[6]) to attempt to minimise the effects of erosion, and these are also being monitored. This multi-measure approach provided good resilience to the rising sea level and is "low regret" in the sense that the adaptations provide other benefits such as recreational facilities and Natura 2000 sustainability.

Effect of Uncertainty on Decision-Making

"Time is needed to convince a community that changes should be sustainable"

The project did not evolve exclusively from a need to consider climate change, but impacts related to sea-level rise, such as erosion and flooding, were key drivers. The Community of Communes wanted a long-term solution to the problems and found that the best way was to produce defences high enough to deal with all eventualities. This solution was a "low regret" solution as it also provided biodiversity, economic and recreational benefits. Exchanges between the project leader, expert and the regional DRM unit have helped to consider sea level rise in a pragmatic way.

The Community of Communes has been able to propose an amended solution to the local problem. Dunes were previously considered obstacles to the development

[6]The geotubes are sediment-filled sleeves of geotextile fabric and used to build structures such as breakwaters, shoreline protection or island creation.

of tourism and at the beginning of the project some decision-makers just wanted to build dykes to keep the sea at bay. The proposed solution has restored the beach and helped sustain the local economic activity. It also provides the necessary protection from erosion and flooding.

Author: Bertrand Reysset

Links to more information: http://www.thau-agglo.fr/IMG/pdf/Dossier_Presse_Lido_2011-2-2.pdf, http://www.developpement-durable.gouv.fr/IMG/pdf/ONERC_lettre_2.pdf

Data sources: DGEC/ONERC (2010), *Prise en compte de l'élévation du niveau de la mer en vue de l'estimation des impacts du changement climatique et des mesures d'adaptation possibles,* Synthèse n°2, 6 p. http://www.developpement-durable.gouv.fr/IMG/pdf/synth_niveau_mer.pdf

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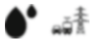
4.2.8 Québec Hydro-Electric Power

Key Messages

Country: Canada

Sector: 

Scale: Regional

Organisation: Public (State-owned)

Decision-type: Strategic

This case study was designed to determine whether climate change should be taken into consideration when developing a hydro-electric power plant refurbishment strategy.

Key messages from this project were:

- The realisation by the hydropower company that there was no such thing as a single "best (climate change) scenario" and that multiple scenarios should be used to deal with climate change uncertainties.
- Clear communication between the climate scenario developers and the operation management and openness to mutual knowledge transfer were most important in the outcome of the project.

Fig. 4.22 Manic 2 Power House on the Manicouagan River (Source: Hydro-Québec)

Background

"There is no such thing as a single "best" scenario in climate change"

After several decades of operation, a number of dams and hydropower stations of the state owned company, **Hydro-Québec** needed refurbishment (Fig. 4.22). Changes in climate have already and will further affect the flow regimes of the dammed catchments. For example, until now winter precipitation has largely been snow, but this is now changing to include rain which ideally needs to be harnessed.

Hydro-Québec, was the primary stakeholder of this project. Their research division, IREQ (Institut de recherche d'Hydro-Québec), conducts research into energy related fields including the assessment of climate change impacts on the watersheds of their power generation stations. However this time it was the operation management who took the step to request concrete climate change information.

The company wished to update its generating equipment to provide state of the art facilities. As part of this process it wanted to evaluate future hydrological conditions to determine their effect on plans for renovation. If they established that climate change was likely to affect their long-term decisions, they planned to carry out more

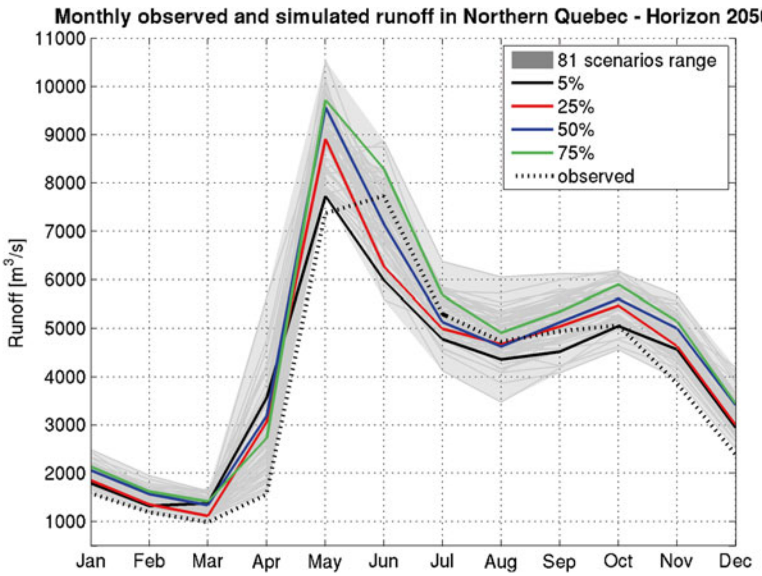


Fig. 4.23 Annual cycle of observed and simulated runoff in a northern Québec watershed. The presently observed runoff is shown as the dashed line. The four selected future scenarios representing the 5th, 25th, 50th and 75th percentile of the range of projected change are shown in colour over the range of all scenarios used. The selection was based on cluster analysis of multiple indicators critical in dam operation and management

in-depth studies of the impacts for specific catchments and sites to be modernised. Their initial approach was to base their study on the "best (climate change) scenario". However, following involvement in meetings and workshops it eventually became clear to them that climate system and projection uncertainty cannot be considered using a single scenario. A sound approach was then developed to review climate change effects under a broader range of conditions. In the end the economic impact study utilised four different future hydrological scenarios.

Process

Initially, a request was made to the Ouranos Consortium, a private, non-profit making organisation advising in the areas of climate sciences, impacts and adaptation, for the "best climate change scenario" to help the company with their plans for plant refurbishment. This resulted in an investigation into climate simulation data and their hydrological impacts and after many meetings and exchanges about the needs of the stakeholder, four projections, representing the 5th, 25th, 50th and 75th percentiles of the range in uncertainty were asked for by the client and as such provided. This is demonstrated in Fig. 4.23 showing changes in runoff.

The work was shared between the Ouranos Consortium who produced the climate scenarios and IREQ who did the hydrological modelling. Clear communication and

Climate data used

- 81 climate simulations composed from:
  - 73 global climate models from CMIP3 (scale approx. 250×250 km)
  - 8 regional climate models from Ouranos CRCM4 simulations (scale 45×45 km)
- Climate variables used to drive a hydrological model: daily precipitation, minimum and maximum temperatures

openness to mutual knowledge transfer were key to the results. For the production of hydropower, precipitation in combination with temperatures is the key climate vulnerability. The meteorological variables were transformed into stream flow using a hydrological model and the four percentiles described above were selected to cover the uncertainty. The final economic evaluation was done by Hydro-Québec in order for them to decide if there was enough change to affect their investment in infrastructure.

A short description of the study was presented outlining the general impacts of climate change on hydrology in the north of Québec.

Risks for hydropower production under different future hydro-climatic conditions include a loss of efficiency of old installations and possible complications in the management of the available water. For example, a release of excess water in the reservoirs would mean a loss of hydropower production. In refurbishing their installations, Hydro-Québec was trying to cope with these vulnerabilities and risks.

Example of handling uncertainty: Multi-criteria cluster analysis

An ensemble of 81 climate simulations was analysed for 11 watersheds. Daily values for each watershed were bias corrected and used to drive a hydrological model to obtain future stream flow scenarios. They were then filtered in a multi-criteria cluster analysis to represent the 5th, 25th, 50th and 75th percentiles of the range of uncertainty in the hydro-climatological projections. Cost-benefit analyses were then performed using these four different hydrological scenarios. In this manner the range from 5 to 75 % (=70 %) of the uncertainty was effectively addressed.

Uncertainty Assessment

The uncertainties taken into account in this study included:

- GHG emission scenario uncertainty,
- Climate model uncertainty,
- Climate system uncertainty,
- Regionalization uncertainty.

Different possible developments of future societies were accounted for by using three GHG emission scenarios in the climate simulations ensemble. Climate model and climate system uncertainty were addressed by including multiple simulations from 16 different global climate models and one regional climate model. Uncertainty of regionalisation of the scenarios was accounted for by using four different empirical downscaling methods in the production of regional hydrological scenarios.

The methods used to analyse the different types of uncertainties were as follows:

- Project scenario analysis (see box),
- Expert elicitation through consultation with the Atmospheric Sciences department at Université du Québec à Montréal,
- Sensitivity analysis of bias correction methods/empirical downscaling,
- Multi-model ensemble using the maximum number of models possible,
- Stakeholder involvement between parties at Hydro-Quebec and Ouranos.

Example of handling uncertainty: Project scenario analysis

Eleven different watersheds had to be identified and analysed. In some cases watershed boundaries had to be re-examined in order to be correctly modelled and to obtain optimal observational data for the empirical downscaling. These iterations were needed to set up the physical description of the problem. Then, the options of covering uncertainty using different numbers of scenarios were played through to demonstrate that the request of "the best scenario" might be over simplified.

By employing exclusively Hydro Québec's operational hydrological model, the uncertainty from hydrological model choice could not be considered. This would require a hydrological model ensemble. Likewise, it was beyond the scope of this study to relate the magnitudes of uncertainty from climate change projections to those from cost-benefit analysis. Both issues are important but relatively new fields of research and shall be addressed in subsequent, more detailed assessment.

Effect of Uncertainty on Decision–Making

Uncertainty has had a profound effect on the course of this study, commencing with the realisation that more than one climate change scenario needed to be taken into account.

The four selected scenarios were used as varying assumptions for a cost-benefit analysis to assess the impacts of increased runoff on hydro-power assets. Based on the results of this analysis the stakeholder has decided that the impacts of climate change are of a magnitude that need to be taken into account in the planning of renovations of hydropower facilities. Thus, more in depth studies of climate change impacts will be conducted and Hydro-Québec will be reviewing its position in more detail to achieve a clear picture of cost-benefit options due to climate change impacts.

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4.2.9 Austrian Federal Railways

Country: Austria
Sector: 
Scale: National
Organisation: Public
Decision-type: Operational+Strategic

Key Messages

"Give information to those who need it"

This case study focused on adaptation in railway infrastructure and how uncertainties in future climate need to be properly considered when time-scales of 100 years are involved.

The key messages are:

- Trend analysis is a useful way to handle uncertainties.
- Constant feedback between company staff and experts is necessary throughout the process.
- Messages must be communicated clearly and in a language which matches the stakeholders language, particularly concerning uncertainties.
- Climate change is usually just another uncertain issue amongst others that companies have to handle traditionally.

Background

"Try to be practical"

The **Austrian Federal Railways** (ÖBB – Österreichische Bundesbahnen) runs the national railway system of Austria. It is entirely owned by the Republic of Austria and is divided into several separate businesses that manage the infrastructure and

Fig. 4.24 Winter service ÖBB – West part of Austria in January 2012 (Photos: ÖBB)

operate passenger and freight services. Since 2003 it has also run Austria's largest bus company with its intercity networks (Fig. 4.24).

The ÖBB is a significant organisation, carrying about 450 million passengers a year. It has about 4,800 km of route network and more than 1,000 railway stations. Given the long life-span of up to 100 years in investments in major transport routes, bridges, tunnels etc. the ÖBB recognised the importance of properly considering changes in future climate when making decisions. After all, the company knows only too well that there is little tolerance from passengers towards the late running of trains.

In 2010, the company contracted the Austrian Environment Agency to help identify potential climate change impacts on rail infrastructure and develop recommendations for adaptation. The aim was to investigate as many meteorological variables and climatic changes as possible that might have an impact on the company's infrastructure and security of service. The company wanted to find practical solutions for problems, whilst taking into account the best scientific knowledge available. The ultimate goal was to incorporate the findings in the company's long-term risk strategy.

Process

"Maintain constant feedback throughout to achieve a robust outcome"

The company was not new to the concept of uncertainty, partly because Austria is an alpine country and used to natural hazard management. They had realised uncertainty is not exclusive to climate change and already affects current decisions in natural hazard management.

Senior executives and company experts in the fields of research and innovation, natural hazards and sustainability were assembled into a steering group and included in every step of the project. Such continuous involvement by company staff in the project was seen as critical to its success. Experts from the Institute of Meteorology at the University of Applied Life Science were part of the project team, also participating in the steering group.

The project focused primarily on climate related risks and the company representatives were generally open and very interested in such matters, being aware of the impact that weather related events can have.

The steering group met approximately every 2 months and this close cooperation between experts with vital information was important to the success of the project. Three workshops were also held to involve other members of the company and discuss the following topics:

- Climate change impacts on railway infrastructure – discussing the overview table.
- Vulnerabilities with specific focus on natural hazards – using trend analysis from company data. It was during this discussion that concerns about uncertainties were addressed with one stakeholder declaring "*You can't tell us what will happen in 2020 in region xxx, so how should we know what to do about this?*" The company's pragmatic answer to this was to provide clear guidance to staff required to implement decisions.
- Climate change adaptation options – dedicated to presenting possible options for the future and getting feedback from the stakeholders.

Climate data used

Regionalised climate scenario were based on ECHAM5 and HADCM3 models and A1B and B1 IPCC GHG scenarios

The first step was to produce an overview table on observed climate impacts for railway infrastructure and some operational issues. This was based on qualitative information stemming from research projects, grey literature and other information sources, and was used as the first basis for the discussion with company representatives. Past observations and stakeholder knowledge were combined with expert judgements using regional climate data so that important climate related impacts and trends could be identified for the ÖBB. In addition, past trends were extracted from company data to see if there were links between disturbances to operations and meteorological events (see Fig. 4.25).

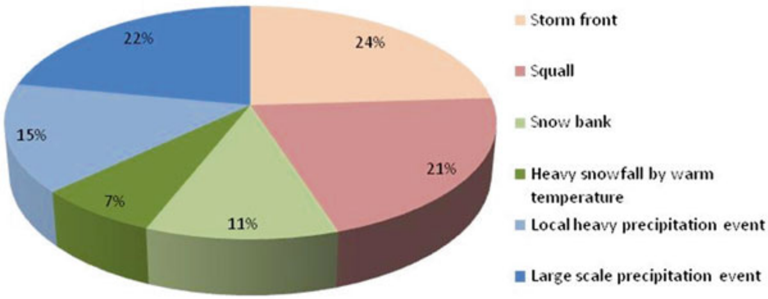

Fig. 4.25 Disturbance cases between 1990 and 2011 clustered by meteorological events (ÖBB data analysed by H. Formayer)

Uncertainty Assessment

It became obvious during the course of the project that dealing with the following uncertainties were key for a good and robust result:

- Uncertainties inherent in climate scenarios (emission scenarios, global models, regional scale issues, problems with consistency of data series). These were dealt with by involving an expert climate meteorologist and working with trend analysis.
- Changes in method of data selection and documentation in the ÖBB internal database on past natural hazards which were used for the trend analysis. Sensitivity analysis was applied to this data.
- No regret/low regret analysis: The Environment Agency collected adaptation options from the literature and highlighted if these options were no-regret or low-regret. The list was discussed with the company's staff to understand if the options would benefit the company and if they could be connected with already existing measures. Considering uncertainties involved, the flexibility of the options was assessed as well.

Handling uncertainty – Trend analysis

More than 1,000 events over the previous 20 years were analysed and compared to parameters such as heavy precipitation, high winds or excessive temperatures responsible for causing disturbances. This formed the basis for the vulnerability assessment and the determination of future trends, although there was some concern over the integrity of this database. Future trends in climate parameters and thus impacts on infrastructure (e.g. rail buckling, infrastructure damage due to floods, storms or heavy snow fall) were then determined based on available regional climate models and expert knowledge.

Other methods of handling uncertainty included:

- Stakeholder involvement

Effect of Uncertainty on Decision–Making

"Implement now to avoid greater costs in the future"

"Nobody knows what will really happen so it is safer to act now"

The project had two very positive outcomes. Firstly, future investment will be climate-proofed; due to the uncertainties in future climate projections, it was decided that planning new infrastructure should not focus on one single "optimal" solution but should be made more robust by taking into account a range of possible climatic changes. Thus, in the case of transport infrastructure, multiple-benefits, no-regret and low-regret adaptation options were recommended.

One example is that of future track drainage. Trend analysis showed that in certain regions future rainfall may become more intense. To cater for this, track drainage will need to be improved. The company reviewed the range of likely outcomes and decided drainage should be improved in some regions to cover all likely eventualities.

Secondly, there was improved sensitivity to climate issues; having experienced the project process, company representatives have built climate change issues into their long-term strategy and developed a sound basis on which to consider such issues in the future.

Author: Andrea Prutsch

Links for more information: http://botany.uibk.ac.at/neophyten/download/09_OeBB_Rachoy_KLIWA.pdf, http://www.oebb.at/infrastruktur/__resources/llShowDoc.jsp?nodeId=29841913

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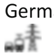
4.2.10 Dresden Public Transport

Country: Germany
Sector: 
Scale: Local
Organisation: Public
Decision-type: Strategic

Key Messages

This project helped refine the current business strategy of a public transport provider in Dresden, Germany to take into account the future effects of climate and demographic change.

Key messages are:

- New tools, such as fuzzy cognitive maps, help clarify uncertainties and identify appropriate strategies within an environment facing a complex mix of challenges.
- Company executives were stimulated to consider the implications of climate change amongst other uncertainties in their decisions.

Background

"An expert partner in the project is crucial"

Public transport is highly sensitive and vulnerable to external impacts which affect the complex relationship between infrastructure, technology, time schedules, and volatile customer behaviour. In a dynamic developing city, the public transport provider needs to deal with changing conditions. Uncertainty in investment funding from the public budget as well as the high dependency on political decisions means that constant planning and refinement of plans is needed.

Climate change primarily impacts this industry through extreme weather events; inherent uncertainties in these have a big influence on both the planning of infrastructure and daily operations of the business. For example, a major flood in 2002 caused roads to be closed and damage to infrastructure which had a long-term impact on the public transport system (Fig. 4.26). Then, in 2003, a heat wave with extreme high temperatures caused discomfort for customers and drivers in buses and trams without air conditioning. In addition, storms, heavy snow fall or ice on the overhead wire can disrupt operation or cause damage through fallen trees etc.

The main goal of the case study was to refine the company's business strategy in the face of future challenges such as climate and demographic change. The company has already taken action to adjust the time schedule of trams and buses in the winter season to handle the possible impacts of continuing snow fall. Economic and technological challenges, such as the increase of energy prices, have also been considered through the introduction of buses with hybrid technology.

Fig. 4.26 Impact of major flood in Dresden in 2002

The project was conducted as part of REGKLAM, an integrated regional climate change adaptation program. It is part of KLIMZUG financed by the German Federal Ministry of Education and Research, involving partners from politics, administration, business and science. The case study itself was run by Technische Universität Dresden (TUD) (under the lead of Chair of Environmental Management and Accounting) and involved the two CEOs of the company along with representatives from company departments such as strategic planning, financial control and human resources. There was considerable understanding within these departments of the negative impacts that climate change is having on the day-to-day running of the transport system through the increase in extreme weather events. The objective was to discuss the final results with the city government to plan for a resilient public transport system.

Process

Figure 4.27 presents the process that was used in the project to develop and use/transfer scenarios in an iterative way. The process began with a kick off meeting in August 2011 to determine the goals. Then, after some desk research, a number of workshops were held, first with experts and then with company representatives, to select key climatic and non-climatic challenges and to analyse the future

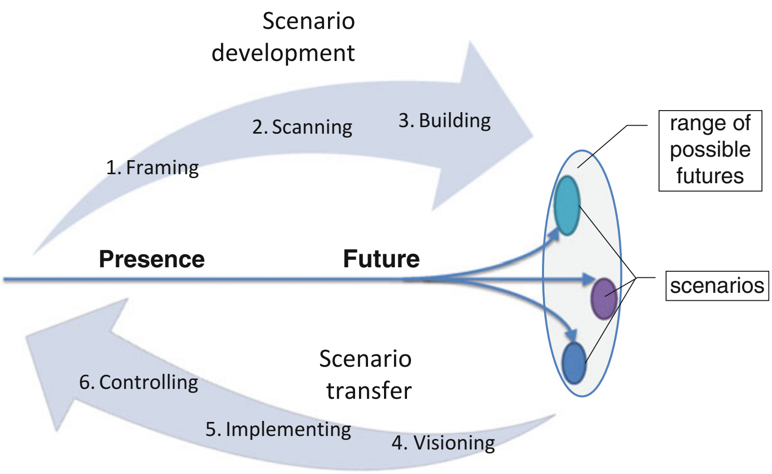


Fig. 4.27 Iterative development of scenarios

development of their associated uncertainties (e.g., climate or demographic change). Accordingly, up to three assumptions for the future development of the key challenges were defined. Various scenarios are developed from this by applying different assumptions to potential pictures of the future. These possible futures will be discussed in workshops with senior executives and options for adaptation identified. The project finished mid 2013.

Climate data sources

- Historic data from the Met Office
- Forecast data using climate models WEREX IV, REMO, CLM and WETTREG (Met Office)
- IPCC emission scenarios

As part of REGKLAM, data was taken from fact sheets developed by the chair of meteorology of TUD. These gave historic data for two time periods up to 2005 for important regional and local climate parameters such as average temperature, average precipitation, dry and hot weather days. They also provided ranges of forecast data for two further time slices up to 2100.

From discussions with company executives however, it became clear that interest was particularly focussed on extreme weather events as these are likely to have the biggest impact on the business. Information was taken from the literature and the whole business environment was scanned. In a first step all potential challenges – 60 in total – were identified and categorised. These were reduced to 19 which particularly affect this public transport sector in order to tackle the problem.

Uncertainty Assessment

Uncertainty in dealing with extreme weather events exists to the extent that no assumptions or prognoses can be made for their future occurrence. The meteorologists in the project developed prognoses for average temperature and precipitation, but they were not able to make such "assumptions" for the occurrence and impact of extreme weather events. The uncertainty related to incomplete knowledge of such events on business challenges was therefore addressed through the use of Fuzzy Cognitive Mapping.

Nineteen climatic and other business challenges were identified in workshops with the stakeholder using Fuzzy Cognitive Maps (Fig. 4.28), with some of the influences described in full below. Possible relationships between the influence factors were identified and assessed according to the strength of the influence. For example it can be seen that extreme weather events such as heavy precipitation, floods, heat waves etc. (EXTWE) have a great influence on the development of information/communication/distribution systems (ICDSY).

Influence factors that have a significant effect or are highly affected by others within the whole system were selected as major key challenges for the next step in the process. Examples included an increase of extreme weather events, changes of customer behaviour, an increase in the development of technologies, and increasing political influence. In this way important relationships between factors affecting a business are identified and the uncertainties are reduced by dealing with these complexities.

The company felt that, through the use of the fuzzy cognitive map, the project provides a clear view on the connections between all factors that influence their business and on the possible effects of their decisions. They feel that it will ease their selections between different options for decision making.

Other methods of handling uncertainty were as follows:

- Scenario analysis ("surprise-free"),
- Expert elicitation,
- Sensitivity analysis,
- Stakeholder involvement,
- Wild cards/surprise scenarios.

Effect of Uncertainty on Decision-Making

"Time is needed within the process to pause and reflect"

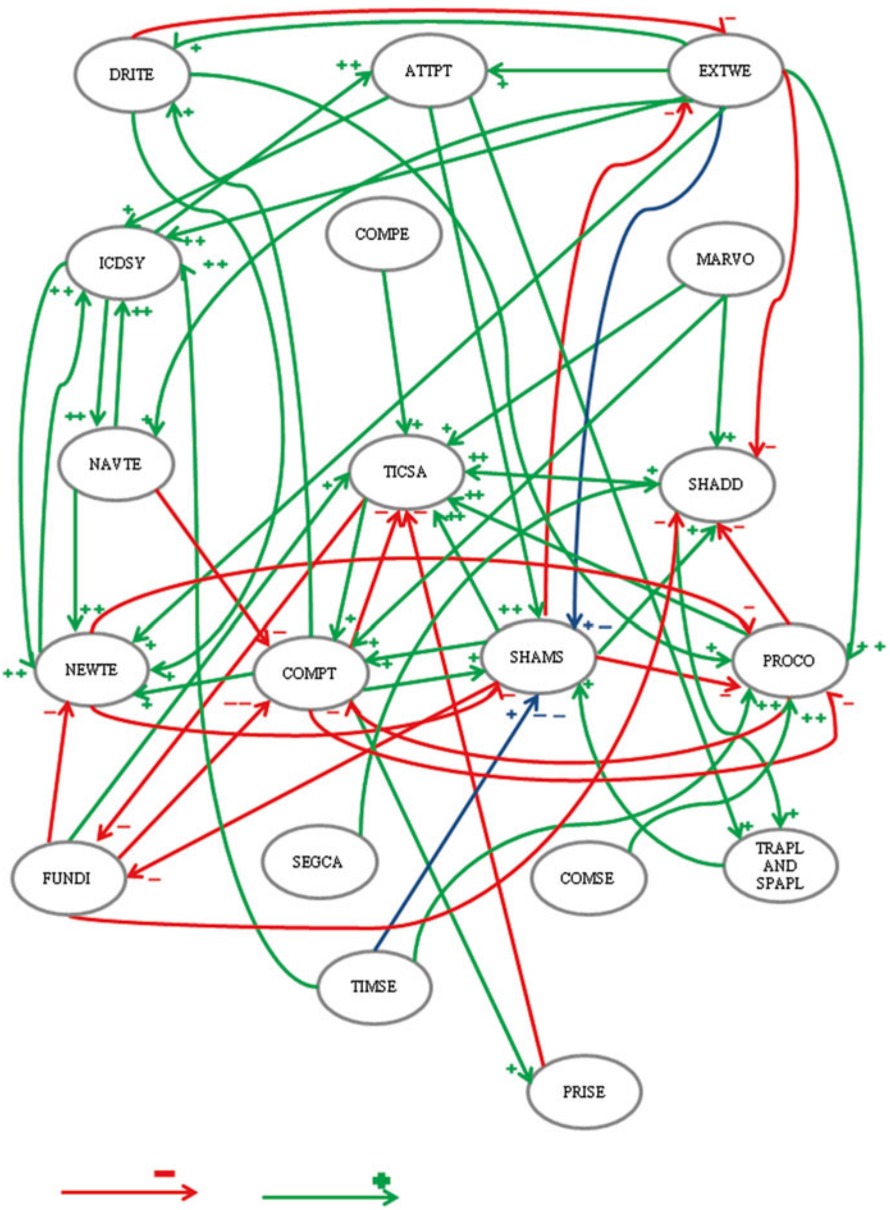


Fig. 4.28 Fuzzy Cognitive Map indicating relationships between influencing factors. *Green arrows* show positive influences and red negative ones. *Blue colour* stands for a relationship that can be both positive and negative. Fuzzy Cognitive Map influences: *EXTWE* Occurrence of extreme weather events, *TICSA* Ticket sales and revenues, *SHADD* Shareholder expectations of deficit development, *NEWTE* New technologies, *COMPT* competition within the public transport community, *SHAMS* share in the modal split, *PROCO* procurement cost, *ICDSY* information, communication, distribution systems, *FUNDI* Funding, *PRISE* Price sensitivity of customers, *TIMSE* Time sensitivity of customers, *COMSE* Comfort sensitivity of customers, *TRAPL* Traffic planning, *SPAPL* spatial planning, *SEGCA* Segregation of duties to the commissioning authority, *NAVTE* Navigation technologies, *MARVO* Market volume, *ATTPT* Attitudes/public transport supporters, *DRITE* Drive technologies or fuels, *COMPE* Compensation

By analysing the whole business environment and identifying the major future challenges, the managers and decision-makers were encouraged to think creatively. This led to a new view on existing strategies and actions and stimulated action to address the associated uncertainties.

The company is very aware that some issues will be strongly influenced by climate and climate change mitigation. For example, diesel engines will disappear in the future, but no-one can yet say what will replace them. Therefore, they need to be involved in the research process. The company culture demands that time is allocated to allow ideas, options and tools to become integrated into general practice. New methods and tools for strategic planning and long-term thinking were introduced and the end result will be an implementation plan for climate change adaptation measures.

Authors: Julian Meyr and Edeltraud Guenther

Links to more information:
For information on the institution leading the case study: http://tu-dresden.de/die_tu_dresden/fakultaeten/fakultaet_wirtschaftswissenschaften/bwl/bu/
For information on the background to the project*:* www.regklam.de

Contact details: ema@mailbox.tu-dresden.de

4.2.11 Hutt River Flood Management

Country: New Zealand
Sector: 
Scale: Local
Organisation: Public
Decision-type: Strategic

Key Messages

"Better to consider a full range of uncertainties now than to put off action until the future when costs will be higher"

"Uncertainties cannot be dismissed as an area scientists don't understand"

This project aimed to improve the understanding of flood risks under the uncertainties of a changing climate in a river basin in New Zealand.

Key messages from the project are:

- The traditional tendency to project historical experience forward is a poor strategy in an uncertain climate because the future is unlikely to be like the past.
- Studies of uncertainties can expose the limits of static flood protection and of emergency planning. Understanding this increased practitioners and community consideration of a wider range of options and adaptive management in space and over time.
- Simple models can be used to explore uncertainties at low cost.
- A workshop process helps increase awareness of uncertainties in future flood risk and their planning implications and influence responses.
- Visual depictions are a powerful way to communicate the effects of climate change uncertainties.

Background

The aims of the project were to:

- Find a simple and low cost method of characterising the effect of climate change on flood frequency across a range of possible futures, and
- Demonstrate whether this influenced understanding and responses to changing flood risk.

The traditional way of using best estimates as single numbers or averages mischaracterises the range (uncertainty) and especially damaging extremes, thus entrenching the perception that protection structures offer safety for long-lived settlements and infrastructure. The project highlighted residual risks to settlements above design flood levels which increase with climate change. It was applied to the Hutt River basin, assessing flood frequency and potential damages of increased inundation levels with climate change. The project was run by the New Zealand Climate Change Research Institute at the Victoria University of Wellington, funded by the government Ministry of Science and Innovation. The primary stakeholders were the Greater Wellington Regional Council and Hutt City Council.

Flood risk is enhanced by climate change and there are substantial risks to urban communities which vary according to socio-economic status and ethnicity. Current methods used in flood risk management in New Zealand do not account for the effects of climate change on flood frequency and in particular, do not consider extremes which represent the uncertainties across the range of future changes. Until now, councils have taken a static, inflexible approach to climate risk in their flood management which has had the effect of entrenching and exacerbating this risk. In addition, averages and single scenarios are often used which underestimate extremes. Consequently, design flood levels used for flood risk management can result in inadequate protection for changing climate risk and give rise to a false sense of security to decision-makers and their communities. A more nuanced, risk-based approach to the effect of changing climate on flood frequency requires consideration of a wide range of alternative scenarios, but this is often constrained by the high cost and complexity of modelling. This project illustrates a simplified approach for evaluating uncertainty in future changes in flood frequencies based on different climate change scenarios, using the Hutt River in New Zealand's lower North Island.

Process

The case study comprised three parts:

- Modelling the effect of climate change on the Hutt River flood frequency and the potential damages from resulting inundation,
- A survey of households on how they responded to flood risk and their views on future climate change induced flood risk,
- A workshop with practitioners across a number of councils in the Wellington region and follow-up interviews with a sample of them.

Climate data sources

- Historical flood data (1972–2008)
- 12 GCMs, statistically downscaled
- Four different emissions scenarios
- An algorithm to infer changes in extreme rainfall based on changes in monthly mean climate

The model used 48 downscaled scenarios to derive changes in monthly average rainfall and temperature in the Hutt river catchment. From these, a simple algorithm determined changes in extreme rainfall which were run through a hydrological model calibrated to the Hutt River.

The results were tested at the workshop to gauge how the participants would respond. Participants included local government practitioners across strategic planning, urban planning, engineering, hazards management scientists, emergency management, and flood management, being those most involved in decision-making on flood risk. The uncertainties were presented visually as a changing risk. This increased the awareness of the participants to a range of possible futures, especially the damage consequences at the extremes, and the need for them to consider a wider range of more flexible responses. They realised that considering the uncertainties more transparently could potentially affect the design and planning assumptions over the life of the flood protection structures. This could thus reduce the risk to the people and assets currently protected. Presenting the dynamic nature of the risk in descriptive and visual form focused the thinking of the participants on the implications and their possible responses.

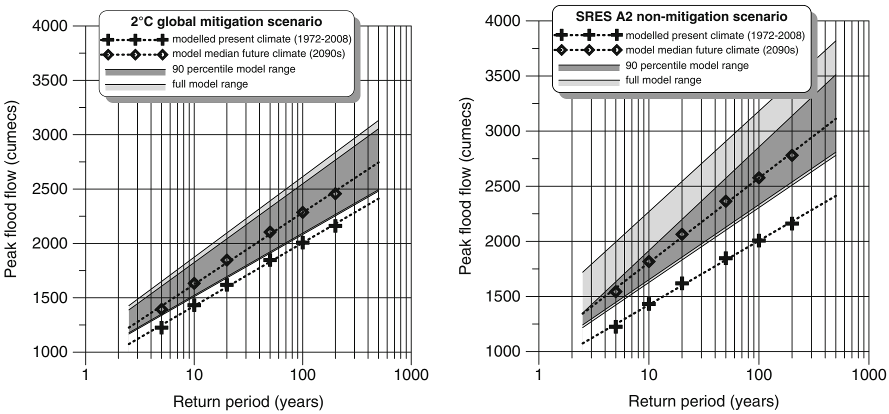


Fig. 4.29 Changes in exceedence probabilities under different emission scenarios. The *black dots* and *solid line* show estimated exceedence probabilities for a range of design flood volumes. The *dotted line* shows the flood volumes for alternative emissions scenarios in 2090 (*left*: 2 °C stabilisation; *right*: A2 SRES emissions) for a range of climate models. The *light grey* band shows the full model range, whereas the *dark grey* band shows the 10–90 percentile model range. A return period of 100 years in the *left hand graph* becomes 30 years and for the *right hand graph* becomes 20 years

The risk context of the visual presentation also resonated with elected councillors. A time and functional element to discussions was introduced, whereby the participants could identify activities with different lifetimes and conceive that changes could be staged over different timeframes to address the changing risk. This was effectively a discussion of adaptive management.

Uncertainty Assessment

The prime uncertainty addressed in this study was the effect of climate change on flood frequency, especially at the extremes. A quick and relatively low-cost methodology to explore the implications of alternative climate change scenarios for flood frequency was presented and applied in a stakeholder workshop setting. Exceedance probabilities, as shown in Fig. 4.29, appeared to increase under all scenarios but with considerable differences between alternative emissions scenarios and climate models. Understanding the full model range and how it changes in frequency emphasises the importance of low probability high impact events for planning and design of responses.

The approach used to assess the potential changes in flood frequency through to the 2090s comprised three steps:

- Statistically downscaled 12 GCMs and four emissions scenarios were used to produce 48 alternative climates (i.e. changes in *monthly average* rainfall and temperature) over the twenty-first century for the Hutt River catchment

- A simple procedure (algorithm) was used to estimate changes in *extreme rainfall* for the catchment
- Hourly rainfall data was run (both historical and adjusted for future climate changes in both means and extremes) through a hydrological model to derive flood frequencies under historical and 48 alternative future climates.

Stakeholder consideration of uncertainty

Flood frequency information affected by climate change was presented visually to participants from councils in the Wellington region. This resulted in participants questioning their reliance on flood warnings, emergency management and levees. The information focused attention on a wider range of complementary response options including protection, accommodation, spatial planning and retreat and the timing of different decisions.

The analysis represents a key advance on those earlier studies in that it quantifies uncertainties in the projected changes depending on emissions and climate models. This supports a more risk-based assessment of impacts and response options and avoids a premature collapse of a range of futures into single estimates, or reliance on simple scaling of current flood volumes that may not account for non-linearities and thresholds in catchment hydrology.

The following methods were used in combination for analysing uncertainty:

- Scenario analysis,
- Sensitivity analysis,
- Probabilistic multi-model ensemble,
- Stakeholder involvement.

Effect of Uncertainty on Decision-Making

"Studies such as these can increase a community's acceptance of a wider range of appropriate options"

This project has catalysed a shift in thinking from static safety and path dependency, to thinking about how to build flexibility into decision-making. For example, a realisation that the bottom of the Hutt catchment could face risks from increased runoff and rainfall, sea level rise, and storm surges, has led to a sharper focus on managed retreat as an option for one low-lying area. The Greater Wellington Regional Council, responsible for the Hutt river management, is including the findings of this study in a review of their flood risk management plan. They have also used the results to discuss a wider range of response options with the local council in the area of the Hutt valley.

Fig. 4.30 Flooding of the Hutt river

Modelling a range of possible futures and showing how a changing climate could affect flood frequency has enabled stakeholders to see the value of the approach developed for their consideration of future risk. Within the community there is an expectation of continuous structural protection. Examination of uncertainty however, exposed the limits of static protection and enabled practitioners to more seriously consider complementary measures that could address changes in climate impacts. These limits may include the costs of raising higher levees and of higher residual damage, as extreme events increase in frequency and intensity and design levels are exceeded. The need for continuous consideration of changing climate risk was also highlighted.

Feedback received from the local government organisations was very positive. They felt it gave them a framework to think about changing climate risk, allowing them to quickly scan responses and discuss them with the elected councillors and local urban councils to consider the implications for a range of options, their costs and timing to enable uncertainties to be a catalyst for decision-making for the future (Fig. 4.30).

Author: Judy Lawrence

Links to more information:

Reports from the research programme can be found here: http://www.victoria.ac.nz/sgees/research-centres/ccri/ccri-publications

The Ministry for the Environment Guidance on the effect of CC on flood flows and which includes the methodology that we used to generate the effect for the Hutt Valley can be found here: http://www.mfe.govt.nz/publications/climate/climate-change-effects-on-flood-flow/tools-estimating-effects-climate-change.pdf

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4.2.12 *Communication of Large Numbers of Climate Scenarios in Dutch Climate Adaptation Workshops*

Country: Netherlands
Sector: 
Scale: Regional/local
Organisation: Public
Decision-type: No decision

Key Messages

This study used workshops to discuss climate change impacts on spatial planning. Climate uncertainties were addressed by means of scenario analysis and different ways of visualising scenario outcomes were tested.

Key learning experiences are:

- The method of presentation of climate change scenario information is key to the understanding of decision-makers.
- Interactive forms of visualising scenario outcomes allow stakeholders to handle the data themselves and so to better understand the impact.
- Policy-makers have a tendency to focus on the 'middle of the road' scenario, whilst scientists focus on extremes, highlighting the inadequacy of a single scenario map.
- There is a high risk of using a single map as decision makers tend to see this as a prediction rather than a projection.
- The challenge of uncertainty combined with high costs of extreme adaptive measures triggers creative minds to look for innovative alternative solutions.

Background

"Everyone needs to be engaged"

"We need to be prepared for change"

In order to stimulate climate adaptation at municipal level, the Province of Gelderland initiated Climate Workshops in close collaboration with the Alterra Research Institute of the Wageningen University and Research Centre. In the municipal environment, planning choices are made between issues such as housing, transport, water systems and safety, agriculture, recreation and the natural environment. There is a general understanding of climate change and its uncertainties within the population of the Netherlands. However, the workshops set up in this project aimed to enhance local understanding of the issues in order to start the process of developing climate-proof policies and plans.

Alterra was joined by an independent architectural expert and the Wageningen University to facilitate the workshops. The municipalities also played an important role, providing indispensable information on local characteristics of the area, and designing the 'climate resilient' spatial plans. Disciplines represented at the workshops ranged from (waste) water management, to green space and urban planning and infrastructure, dealing with spatial planning and urban design.

Even though the workshops did not specifically focus on uncertainty, dealing with uncertainty was unavoidable.

Process

"Spread knowledge widely throughout the organization"

An initial workshop was held over 3 days in September 2010 to discuss and create plans to climate-proof specific regions (Fig. 4.31). At this meeting the idea of organising further workshops aimed at individual municipalities was generated. It was felt by the researchers and stakeholders present that if you do not spread climate change related knowledge to everyone in an organisation, then it is wasted. Four of these workshops took place a year later in 2011 with further workshops organised in 2012 and planned for 2013. They bring together many influential individuals round a table to discuss what climate change means for their town. They are usually policy- and decision-makers involved in spatial planning, but aldermen, i.e. senior political representatives of the municipality, have been invited as the ultimate challenge is to engage such politicians.

The workshop process can be roughly divided into the following steps:

- Analysis of the potential **climate change impacts** on a municipal level.
- Assessment of the potential **consequences** of these changes for municipal (spatial) plans.
- **Design sessions to adjust plans** to make them more resilient to a changing climate.
- **Review** of the workshop process, making improvements as necessary and discussion of the process of generating climate-proof spatial plans.

Rather than focussing on changing existing plans the workshops aimed to give the participants a feeling for climate change and adaptation. Actual case studies, relating to water conservation, water nuisance from heavy precipitation, urban heat islands and the robustness and connection of natural areas were used to illustrate the position. Participants attempted to answer the question "how could this plan have been designed to be able to deal with projected climatic changes?" Initially

Fig. 4.31 Workshop in progress

information was presented in a PowerPoint format but as the workshops progressed, various visualisation techniques were developed.

All climate information used during the workshops originated from the Climate Adaptation Atlas (CAA). The adaptation atlas is an ever growing web-portal in which many climate impacts relevant for the Netherlands have been visualised in geospatial maps. It contains maps of projected changes in precipitation, temperature, water nuisance, water safety, droughts, urban-heat-islands and the consequences of these changes for agriculture and nature. It forms a solid foundation of knowledge for the development of adaptation strategies.

Four KNMI scenarios

- W: warm (+2 °C)
- W+: warm + changed air circulation
- G: moderate (+1 °C)
- G+: moderate + changed air circulation

Within the CAA climate uncertainties are addressed by means of scenario analysis, based on the four climate scenarios of the Dutch meteorological office KNMI over four different time steps (2020, 2030, 2050 and 2100). It was important to consider an even number of scenarios to avoid the temptation to focus on a mid-range or average scenario. Precipitation, temperature, water nuisance, water safety, droughts, urban-heat-islands and the consequences of these changes for agriculture, for example in the production of maize, and nature are visualised using the resulting 16 maps (or 17 including the current situation).

Uncertainty Assessment

"Interactive tools allow decision-makers to manipulate the numbers themselves"

The difficulty in presenting such a large number of maps encouraged researchers to seek innovative ways of presenting a broad range of scenario outcomes. How well the information was perceived was subsequently reviewed in detail and the following three different visualisation techniques were experimented with:

- Static visualisation – all maps presented on one page,
- Animated visualisation – an animated presentation displaying a succession of the maps – either over time or across scenarios,
- Interactive visualisation – combination of all maps into one tool, providing a menu to allow a switching between the stacks of images.

Of the three methods presented, the interactive tool, as shown in Fig. 4.32, resulted in the quickest solving of the tasks, giving it the highest score for efficiency. The participants were unanimous in feeling that the interactive tool was the most intuitive. They also liked the ability to continuously compare the different scenarios and time steps with the current scenario.

At the start of the workshops most participants had a good basic knowledge of climate change and its consequences for The Netherlands. However, the extremes and possible range of outcomes were often much greater than expected, and seeing impacts visualised specifically for a municipality was often an eye-opener for them. Practice has shown that single maps are often preferred by decision-makers and are used as predictions rather than being used to explore a range of plausible futures. Also, while policy makers might have a tendency to focus on one of the 'middle of the road' scenario outcomes, scientists often focus on the extremes.

As the design sessions got underway the confrontation with a large range of possible climatic changes and high potential costs of extreme adaptation measures,

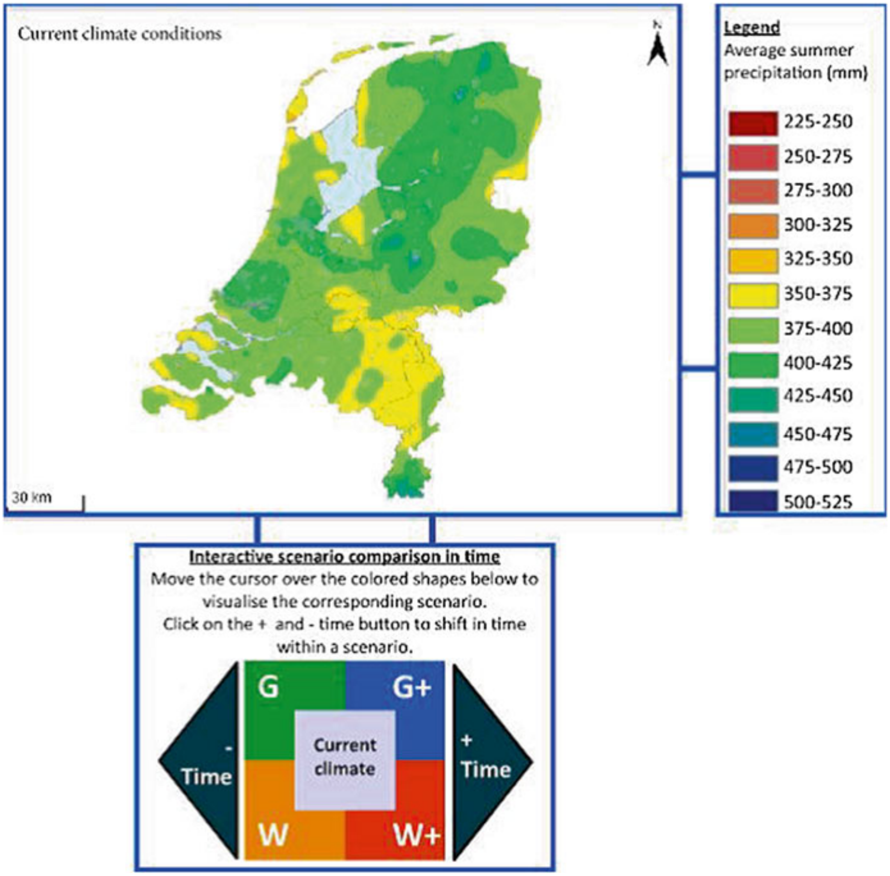

Fig. 4.32 A static representation of the interactive visualisation tool

triggered creative minds to look for innovative, robust measures and to mainstream adaptation measures into other policies. Some examples of this included green roofs as water buffers and insulation, and extra green space in residential areas to increase living comfort.

Effect of Uncertainty on Decision–Making

"Decision-makers need to realise they are not 100 % sure how climate will change"

The project was primarily designed to communicate the problems of climate change and one of the most significant outcomes was that the project improved the way scenario maps are presented. This is critical to ensure decision-makers fully appreciate the implications of uncertainty in the climate data. Three methods of static visualisation, animated visualisation and interactive visualisation were experimented with. First testing shows that most participants prefer the interactive visualisation as it is the easiest way to handle different information and because of its ability to see patterns in time.

The initial central question of the workshops was 'how can we adapt to climate change?' In the course of the workshops and partly due to the use of a range of scenario outcomes the focus gradually turned towards 'what measures can we take that would allow us to deal with the entire range of possible outcomes?' In one workshop an alderman was looking at houses built in a low, flood-prone part of the region and asked "how could we have been so stupid?" This prompted a rethink of the latest proposal to build on even lower ground, and a realisation of the need to be prepared for change, whatever it might be.

Author: Luuk Masselink

Links for more information:

A general description of the workshops organised at regional level can be found at the website of the national climate programmes of the Netherlands: http://www.klimaatonderzoeknederland.nl/projecten/archief-projecten-nieuws/10657914/Klimaatateliers-COM37.

A report of the Climate Atelier Gelderland on a regional scale can be found at the web portal of the Climate Adaptation Atlas: http://klimaateffectatlas.wur.nl.

The Climate Adaptation Atlas is part of the newly founded foundation Climate Adaptation Services: http://www.climateadaptationservices.com/uk/home

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CHAPTER 4: NEW ADAPTATION DECISION-MAKING FRAMEWORKS

Publication IV – Making adaptation decisions under uncertainty: lessons from theory and practice

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This book chapter is published in the Adapting to an Uncertain Climate: Lessons from Practice book and should be referenced as: Capela Lourenço, T., Rovisco, A., and Groot, A. (2014) Making adaptation decisions under uncertainty: lessons from theory and practice, *in* Capela Lourenço T., Rovisco, A., Groot, A., Nilsson, C., Füssel, H-M, van Bree, L. and Street, R. (Editors) (2014) *Adapting to an Uncertain Climate: Lessons from Practice*. Springer, the Netherlands, ISBN: 978-3-319-04875-8, 182pp.

Chapter 5
Making Adaptation Decisions Under Uncertainty: Lessons from Theory and Practice

Tiago Capela Lourenço, Ana Rovisco, and Annemarie Groot

Key Messages

- Uncertainty can be looked upon from three different points of view:
  - It is possible to deal with uncertainties and act in spite of their existence;
  - It is necessary to reduce uncertainties before making a decision on how to proceed;
  - Uncertainties are considered too large and act either as a barrier to decisions or as a motive to postpone them.
- A clear definition of the adaptation decision objectives and scope is recommended. This will improve communication between decision-makers and those supporting them. Ultimately it will also contribute to enhance the communication between decision-makers and those affected by their decisions (like the public in general or relevant stakeholders).
- The use of multiple methods to deal with and communicate uncertainties is recommended. The correct application of these methods should fit-to-purpose, cover a wide range of uncertainty typologies and aim at providing the widest range of support to different decisions and respective information needs, without compromising clarity.

(continued)

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T. Capela Lourenço et al. (eds.), *Adapting to an Uncertain Climate: Lessons From Practice*, DOI 10.1007/978-3-319-04876-5_5,

(continued)

- Uncertainty can (and should) be communicated in a number of ways:
  - Ensure the involvement of decision-makers and transfer of know-how throughout the development of climate risk and adaptation assessments;
  - Guarantee that messages are clearly communicated and in a language that is common to all stakeholders involved;
  - Promote interactive workshops in order to increase awareness of stakeholders involved;
  - Provide guidance on how to deal with the uncertainties that are present in the outcomes of the decision-making support activity;
  - Use visual depictions of results, including associated uncertainties. For example, the use of interactive tools for visualising scenarios allows stakeholders to handle the data as well as to continuously compare different scenarios and time steps. Other methods of providing visual depictions of results include using confidence scales and score-cards, or recurring to uncertainty typology and ranking of risks according to their likelihood and severity.
- The suggested approaches to decision-making are numerous and should be adjusted to each decision context:
  - Prefer approaches that are robust under a wide range of possible futures, have multiple-benefits and that are low- or no-regret;
  - Prefer options that contribute to enhance resilience and adaptive capacity;
  - Opt for strategies that consider a wide range and variety of options and are able to support adaptive management or learning by doing approaches;
  - Favour options and measures that allow for flexibility.

5.1 Introduction

This chapter synthesises some of the theoretical (scientific) and practical aspects of the preceding chapters, draws key lessons and provides guidance for those involved in supporting and ultimately making adaptation decisions.

A Common Frame of Reference (i.e. common definitions, principles and understandings) for dealing with uncertainties in climate adaptation decision-making is presented and applied to the analysis of the twelve real-life cases presented in this book. A summary of its dimensions and key features is shown in Table 5.1.

This new framework, developed under the scope of the CIRCLE-2 Joint Initiative on Climate Uncertainties,[1] intends to serve as a support to complex climate adaptation decision-making processes that have to deal with uncertainties and still make informed decisions.

[1] www.circle-era.eu

Table 5.1 Summary of the Common Frame of Reference dimensions and respective typologies

Dimensions					
	Decision-support				
Decision-objectives	To model or not to model?	Top-down or bottom-up?	How certain am I?	Decision-making	Decision-outcomes
Normative/regulatory	Model based	Predictive top-down (optimization or 'science- first')	Statistical uncertainty	Decision made and implementation agreed	Monitoring and evaluating approaches
Strategic/process-oriented	Non-model based	Resilience bottom-up (robustness or 'decision-first')	Scenario uncertainty	Decision delayed	
Operative/action-oriented			Recognised ignorance	Decision not made or not related to adaptation	

Two central questions were addressed using this Common Frame of Reference and were applied to the cases reported in this book:

- How did the approaches used to deal with climate uncertainty influence the adaptation decision-making process?
- Have better informed adaptation decisions been made because uncertainties were conscientiously addressed?

The objective of this chapter is not to provide a simple checklist to be followed when facing uncertainties in a climate adaptation process. Nor does it dare to prescribe a normative 'right' way to make an adaptation decision in the face of climate and non-climate uncertainties.

The purpose here is to inform and guide our readers in navigating a novel, complex and challenging decision-making area, by presenting key lessons and insights from real-life cases were decision-makers and those that support them have already faced and responded to climate adaptation related uncertainty.

As in many other fields, science can inform but in the end decisions are always taken in a 'lonely place'. Despite different cultural contexts, sectors, conditions and ultimately the types of uncertainties that are faced, adaptation decisions are already being made and will continue to be in the foreseeable future. Therefore, the remainder of this chapter presents the reader with the analysis of some hopefully inspiring lessons and approaches that have been followed to support such decisions.

5.2 A New Support Framework for Adaptation Decisions Under Uncertainty

Science-supported decision-making has been the focus of research in multiple scientific and societal challenges (Adger et al. 2013; Ranger et al. 2010; Willows and Connell 2003). Many environmental, economic and societal decision-making processes as well as their underlying knowledge base, tend to be framed from a particular disciplinary perspective (e.g. natural sciences vs. social sciences; basic vs. applied science; technological or economic vs. environmental focus). Climate and climate change adaptation decision-making processes are not a novelty in this regard.

Experience has shown that implementing and communicating climate change impacts and vulnerability assessments in support of practical decision-making is a significant challenge (Tompkins et al. 2010; Adger et al. 2005). Recent literature, mostly concerned with high-end climate change scenarios (e.g. increase of more than 4 °C in global average temperatures) has highlighted some key gaps.

Firstly, the emerging need for innovative strategies and end-user involvement in the development of uncertainty-management methods (Hallegatte 2009). And secondly, the notion that such methods need to be framed within a broader sorting of decision types and systematised into decision support frameworks (Smith et al. 2011).

Climate adaptation decisions, however, are neither taken in isolation from other factors nor are they immune to changes in context specific situations such as culture, economy, politics, resources, institutions, and geography among others (Adger et al. 2008, 2013; Brien et al. 2004).

Adaptation decisions comprise a high level of uniqueness and solutions have often to be determined on a case-by-case approach. Each decision goes through a unique process of development and implementation (Walker et al. 2003). This raises the question of whether it is possible to extract any comparable and valuable lessons from how other decision-makers across the world dealt with uncertainty and ultimately how they came to their adaptation decisions.

Several attempts have been made at capturing and describing the complexity of science-supported climate adaptation decision-making (including policymaking) processes (Hanger et al. 2012; Ranger et al. 2010; Dessai and van der Sluijs 2007; Walker et al. 2003; Willows and Connell 2003).

Nevertheless, practical experience with national and international decision-makers both in Europe as in other parts of the worlds, have shown us how difficult it is to apply such theoretical frameworks into real-life adaptation decisions. Uncertainties in the evidence and in the application of the necessary knowledge base are obviously not the only reason for concern. Yet they rank high when the question at the table is 'how to make an adaptation decision?' or better yet 'how to implement adaptation in practice?'

If positioned in the broader adaptation process context or, for example, as they naturally occur in a risk management cycle, decision-making processes usually encompass some initial framing of the adaptation problem followed by a set of decision-support activities such as research, consulting or policy analysis, the subsequently making of the actual decision and at a later stage the monitoring and evaluation of the decision's outcomes (Hanger et al. 2012; Kwakkel et al. 2011; Ranger et al. 2010; Dessai and van der Sluijs 2007; Walker et al. 2003; Willows and Connell 2003).

There are some key generic features that can be highlighted across these conceptual descriptions of an adaptation decision-making process, namely:

- Their interactive nature;
- The presence of multiple steps (or stages) and feedback mechanisms; and
- Their growing complexity in number and governance of involved agents (both decision-makers and decision-support agents).

Nevertheless, the entry point to these processes is not necessarily always the same and, in practice, the stages in decision-making will not always follow on from one another. It is often necessary to return to previous steps, e.g., to take into account new options only identified after a first round of assessments or appraisal work (Willows and Connell 2003).

Different systems may also need to be assessed differently and pre-exiting conditions may influence the way a decision-maker acts and goes through this cycle. Furthermore, each decision or policy undergoes its own unique process of development and implementation with the involvement of researchers or other kind of analysts potentially taking many different forms (Walker et al. 2003).

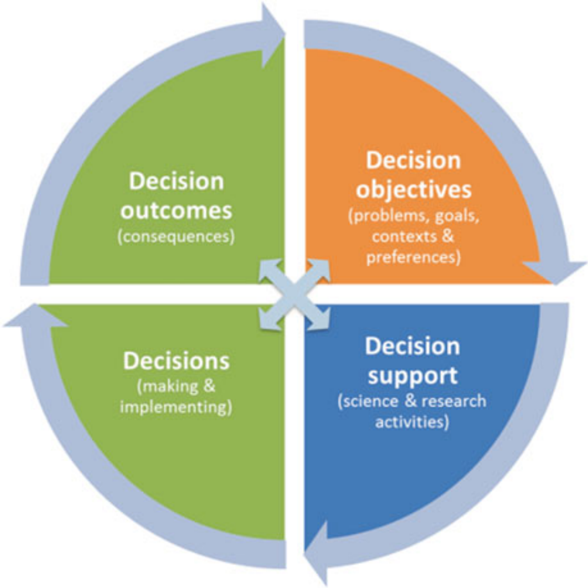

Fig. 5.1 A new Common Frame of Reference for science-supported climate adaptation decision-making (This framework has been adapted and modified from Kwakkel et al. (2011), Ranger et al. (2010), Dessai and van der Sluijs (2007), Walker et al. (2003), Willows and Connell (2003) in order to explicitly accommodate the need to deal with uncertainty in the decision-making process)

Figure 5.1 describes a simplified Common Frame of Reference to be used in the analysis of a science-supported adaptation decision-making process and as a guiding framework to explore the effect of uncertainties in this sort of decisions. It is based on both academic literature and on the practical experience of dealing with adaptation processes in real-life cases.

It does not intend to be exhaustive but rather to provide a flexible and common approach in understanding how adaptation decision-making under climate change and uncertainty develops, in particular when comparing across different decisions types, decision support methods, and variable geographical, socio-economic and cultural realities.

This Common Frame of Reference is depicted in Fig. 5.1 as a generic cycle involving four inter-connected and complementary dimensions, which can be applied to describe necessary steps in this kind of processes:

- **Decision-Objectives;**
- **Decision-Support;**
- **Decision-Making (and -implementing); and**
- **Decision-Outcomes**.

5.2.1 Decision-Objectives

The entry point to an adaptation decision-making process is often connected with the definition of its objectives. This Decision-Objectives dimension relates to the adaptation problem, as well as to the goals, objectives, values and preferences of the decision-maker and those of the relevant stakeholders.

Choices and decisions will affect the structure and/or performance of the system to which they are applied, so contexts are very important and play a determinant role in this dimension. Although sometimes developed in isolation by decision-makers and their support teams, a decision objective is very often discussed with, or constrained by, stakeholders of all sorts.

Trade-offs between different preferred outcomes that determine the objectives are thus quite important, since adaptation decisions usually have multiple outcomes of interest (Walker et al. 2003).

Within this dimension three common objectives for an adaptation decision can be distinguished, each with its own specificities in terms of uncertainty management:

- **Normative or regulatory**, associated with governance actions that aim to establish a standard or norm;
- **Strategic or process-oriented**, associated with the identification of long-term or overall aims and the necessary setting up of actions and means to achieve them;
- **Operative or action-oriented**, related to the practical actions and steps required to do something, typically to achieve an aim.

5.2.2 Decision-Support

The Decision-Support dimension refers to the set of science, research or other types of activities (like consultancy or policy advice) designed and carried out to support the adaptation decision-makers and the problems being considered.

Scientists, analysts, consultants and other expert advisors are frequently called upon to assess and inform the decision-making process. Often this is the dimension where uncertainties are usually explicitly framed and handled. The uncertainty-management methods and tools described in Chap. 2 and the ones applied in each of the case studies of Chap. 4, are a part of this dimension.

This dimension and the way uncertainties are dealt in it can also be associated to the broader adaptation context as it can usually be seen in, for example, a risk management process cycle. Decision support activities are obviously not exclusive to the adaptation context and are carried out in a variety of policy and decision problems. Lessons can also be learnt there.

In this book we aim exclusively at those activities that are directed at the climate adaptation decision-making and at the way uncertainty is dealt in this particular context. Nevertheless, we do not exclude that this framing of decision typologies and uncertainty management could potentially be useful for other areas of policy and business.

Three generic typologies of relevance to this dimension are detailed below:

To model or not to model?

A common approach to decision support is to create a numerical model of the system, defining its boundaries and structure. It is likely to represent the system's elements and the links, flows and relationships between them (Walker et al. 2003).

In this context, this is termed a model-based decision-support that may or may not be a computer-based model. Non-model decision support (e.g. expert judgement or qualitative assessment) is also commonly employed, in particular when the complexity of the system at hand is too large, or the time availability to coherently model it numerically is too short.

For the sake of simplicity we do not consider 'mental models' as used by experts as part of the model-based support systems (see Lowe and Lorenzoni 2007 and Sect. 2.3.1 of this book).

Models may incorporate different types of uncertainty and because of their common use in this field are often singled out by the public and decision-makers as a primary location of any uncertainty-related problem in the underlying knowledge for adaptation.

These concepts are explored in greater detail in Sect. 2.3.1 of this book.

Top-down or bottom-up?

Another common feature of this dimension is the direction of the approach that is applied to support the decision-making process. In other words, it refers to the direction used by the adaptation assessments or other sort of support activities that are carried out, to the way uncertainties are handled in these and ultimately to the advice they produce.

Such direction is usually defined (Ranger et al. 2010; Dessai and van der Sluijs 2007) as being:

- **Predictive top-down (optimisation or 'science-first')**, emphasising the need to 'foresee' future climate changes and handle the associated uncertainty by categorising, reducing, managing and communicating it. Under this approach the adaptation assessment stages usually follow a linear approach from prediction/projection to decision. They usually begin with projections of climate change, followed by the assessment of potential biophysical impacts and later on by exploring a range of adaptation options;
- **Resilience bottom-up (robustness or 'decision-first')**, accepting uncertainties and unanticipated surprises as being potentially irreducible, and emphasising a 'learning from the past' approach. This approach favours an assessment that usually starts with the adaptation problem at hand (including objectives and constrains), followed by the mapping of available adaptation options, and later evaluating these against projections of climate change.

In reality, mixed approaches are applied in support of adaptation decision-making. This is due to the fact that the choice is not usually between which of the two approaches to use, but rather a need to achieve the best trade-off along a continuous scale that balances between optimisation and robustness (Ranger et al. 2010).

These approaches are explored in greater detail in Sect. 2.5.1 of this book.

How certain am I?

The third feature considered under this dimension is the level of uncertainty that is primarily addressed by the decision-making support activities.

Three levels are distinguished in the literature (e.g. Walker et al. 2003) and, despite the complexity of the concepts, can be analysed in practice:

- **Statistical uncertainty**;
- **Scenario uncertainty**;
- **Recognised ignorance**.

These levels reflect where the uncertainties manifest themselves along a spectrum that progresses from a theoretical full deterministic knowledge of a system ('I'm completely certain of what I know') to an extreme of total ignorance ('I don't even know what I don't know').

The three levels mentioned above lie in between these extremes and represent the most current framing of uncertainty, as it can be regularly applied to practical decision-making support activities (even if not explicitly stated since uncertainties are often not acknowledged).

These levels are explored in greater detail in Sect. 2.3.2 of this book.

5.2.3 Decision-Making

This third dimension of the Common Frame of Reference is related to the actual adaptation decision.

Although there are exceptions, adaptation decisions are usually made in relation to the original problem and objectives, after enough evidence or knowledge has been provided to support an informed action by a decision-maker.

In practice, a decision represents a determination arrived at after consideration, and three results can be associated with an informed adaptation decision-making process under uncertainty:

- **A decision about the adaptation problem is made**, based on the information and evidence provided, and its implementation is agreed and pursued taking into consideration existing uncertainties;
- **A decision is made to delay action regarding the adaptation problem**, until more knowledge is available or the uncertainties associated with the current information or evidence are reduced or differently managed;
- **A decision about the adaptation problem is not made (no-decision)** or a different sort of decision (not related to adaptation or contrary to its objectives) is made and its implementation is agreed and pursued.

These determinations represent, in the context of this book, informed and knowledge-supported decisions normally associated with planned adaptation.

Obviously we cannot have the pretension to map all the contexts where adaptation decisions are made. This means accepting that there can be decisions that are made without explicit external support (such as those related to autonomous adaptation) or yet, that many can be biased by a multitude of factors that have nothing to do with the adaptation problem.

It also means to admit that there will be cases where the information that is provided to a decision-maker may not be the correct one or that science may not always be able to perfectly inform a complex process such as this.

Adaptation decision-making is explored in greater detail in Sects. 2.5 and 2.6 of this book.

5.2.4 Decision-Outcomes

The outcomes of an adaptation decision are difficult to assess and evaluate since some time has to pass (shorter for climate variability and longer for climate change) until the consequences of the decision are visible and can be evaluated. This means that it is also difficult to assess the influence or role played by uncertainty-management methods in shaping up these outcomes.

The monitoring and evaluation (M&E) of adaptation decisions and options has gained recent attention as more and more adaptation decisions are necessary. But adaptation is a relatively recent field of research and especially of decision-making and practice. To date the implementation of adaptation decisions is limited and thus there are not that many outcomes easily available and susceptible of being evaluated. The same applies to the role of uncertainty-management approaches in the shaping of these outcomes.

There has been a recent proliferation of M&E initiatives, guidelines and frameworks. A comprehensive overview of currently available material and tools that can be applied to this dimension is provided by Bours et al. (2013).

Like almost all of the known adaptation examples throughout the world, the real-life cases presented in Chap. 4 have not yet reached this stage, at least from a decisions outcome's evaluation perspective. They can however be the subject of monitoring since they represent adaptation problems that have undergone a decision-making process and that, for better or worse, have seen a given course of action being decided.

Because of the novelty of this dimension there are not many approaches readily available to deal with uncertainties, their contribution to adaptation decisions and its outcomes. Nevertheless, adaptive management approaches have been singled out as being particularly relevant to climate change adaptation and uncertainty management.

Following adaptive management approaches, including monitoring, evaluation and learning (including social learning) that build on growing experience and new knowledge, can also assist in progressive reframing. This is of special relevance being adaptation a continuing and evolving process rather than a single project, decision or initiative (Webb and Beh 2013).

5.3 What Has Practice Shown Us?

In order to better understand how others have dealt with uncertainty in their adaptation decisions and if the processes they followed are transferable, comparability is essential. This section presents some of the key findings extracted from the application of the Common Frame of Reference to the twelve real-life case studies presented in Chap. 4. Table 5.2 presents an overview of key elements, across all cases, for the Decision-Objectives and Decision-Support dimensions.

It allows for a comparative assessment and describes how each situation has dealt with different adaptation objectives and different uncertainty typologies, and how the adaptation decision-making was supported through the use of uncertainty-management and communication methods (see Chap. 2 for more information on the underlying theory).

Each of the case studies is unique in the sense that it tells its own story about policy-makers, decision-makers and scientists who jointly tried to handle the uncertainty inherent to climate change science and move into practice by making informed adaptation decisions.

Table 5.3 further extends this assessment to the third dimension of the Common Frame of Reference, the Decision-Making. In other words, it deals with the adaptation decisions themselves. For each practical case key decisions are presented and a short analysis of how uncertainty played a role in the decision-making process is described.

5.4 Dealing with Uncertainty in Adaptation Decision-Making

Despite the need for 'better' science, this is not in itself a sufficient condition (Tribbia and Moser 2008 and Hanger et al. 2012) for 'better' decisions. These can result from decision-making processes that consider and integrate expert knowledge (Lynch et al. 2008; Dessai et al. 2009), allow for the involvement of relevant stakeholders and that take into account both the climate and non-climate factors representing potential sources of risk and uncertainty (Willows and Connell 2003).

There seems to be a growing consensus that decision-makers are longing for a better integration of existing information rather than more or better information (Tribbia and Moser 2008; Hanger et al. 2012). This must also include the way uncertainty is dealt with along the adaptation decision-making cycle and how uncertainty-management approaches may contribute to a better integration of data sources, processes and knowledge.

Table 5.2 Sorting of the 12 real-life cases (Chap. 4) according to the Common Frame of Reference, dimension further includes the methods used to deal with uncertainty in each case

	Decision-Objectives			Decision-Support					
				To model or not to model?		Top-down or bottom-up?		How certain am I?	
Cases (Chap. 4)	Normative/ regulatory	Strategic/ process-oriented	Operative/ action-oriented	Model based	Non-model based	Predictive top-down	Resilience bottom-up	Statis-tical	Scenario
Water Supply Management in Portugal (4.2.1)		•	•	•	•	•	•		•
UK Climate Change Risk Assessment (4.2.2)		•		•	•	•		•	•
Water Resources Management in England and Wales (4.2.3)	•			•		•		•	
Water Supply in Hungary (4.2.4)		•		•	•	•			•
Climate Change and Health in The Netherlands (4.2.5)		•			•		•		•
Flood Risk in Ireland (4.2.6)		•		•			•		•
Coastal Flooding and Erosion in South West France (4.2.7)			•		•		•		•
Québec Hydro-Electric Power (4.2.8)		•		•		•			•
Austrian Federal Railways (4.2.9)		•			•		•		•
Dresden Public Transport (4.2.10)		•			•		•		•
Hutt River Flood Management (4.2.11)		•		•	•	•		•	•
Communication of Large Numbers of Climate Scenarios in Dutch Climate Adaptation Workshops (4.2.12)		•			•	•			•
Total	**1**	**10**	**2**	**7**	**9**	**7**	**6**	**3**	**11**

Abbreviations (see Chap. 2 and Key Terms for more detail): *SA* Scenario analysis ('surprise-free'), model ensemble, *BM* Bayesian methods, *NUSAP* NUSAP/Pedigree analysis, *FZ/IP* Fuzzy *EPP* Extended peer review (review by stakeholders), *WC/SS* Wild cards/Surprise scenarios, for the Decision-Objectives and the Decision-Support dimensions. The Decision-Support

	Methods used to deal with uncertainty												
Recognised ignorance	SA	EE	SENS	MC	PMME	BM	NUSAP	FZ/IP	SI	QA/QC	EPP	WC/SS	Other(s)
	•	•	•						•		•		
	•	•	•			•	•		•	•	•		
				•	•								
		•	•		•			•	•				
•		•							•				
•			•									•	
•		•							•				
	•	•	•		•				•				
		•	•			•			•				
•	•	•	•					•	•			•	•
	•		•		•				•				
	•	•	•						•				
4	**6**	**9**	**9**	**1**	**4**	**2**	**1**	**2**	**10**	**1**	**2**	**2**	**1**

EE Expert elicitation, *SENS* Sensitivity analysis, *MC* Monte Carlo, *PMME* Probabilistic multi sets/Imprecise probabilities, *SI* Stakeholder involvement, *QA*/*QC* Quality assurance/Quality checklists, *Other* Causal and Fuzzy Cognitive Mapping (added by case authors)

Table 5.3 Characterisation and findings for the Decision-making dimension of the real-life cases (presented in Chap. 4)

Cases (Chap. 4)	Decision-Making: Have adaptation decisions been made?	What was the influence of uncertainty management in the adaptation decision-making process?
Water Supply Management in Portugal (4.2.1)	*Decision made and implementation agreed*: Establishment of cooperation protocols with external stakeholders. *Decision delayed*: Investments in nanofiltration systems. *Decision not made or not related to adaptation*: Investment decision on prevention measures against forest fires around key water source.	Different initial views of the company's staff were a barrier to adaptation, but the treatment of uncertainties clarified and improved the confidence in the underlying evidence. Started to use multiple-scenarios in the analysis of climate change impacts and vulnerability of water sources. Strategic and operational decisions based on vulnerability assessments that include uncertainty information.
UK Climate Change Risk Assessment (4.2.2)	*Decision made and implementation agreed*: Official use of results and evidence in national and local support of adaptation decision-making (policy and planning).	Priority risks identified with the recognition that uncertainties need to be considered. Incorporation of flexibility into adaptation policies and planning and respective reporting.
Water Resources Management in England and Wales (4.2.3)	*Decision made and implementation agreed*: Development of guidance on the use of probabilistic climate change information in water resources plans.	Acceptance by both the Environment Agency and water companies that planning based on single storylines is a risk in itself. Water companies' willingness to use results originated in the use of multiple models as long as tools remain simple.
Water Supply in Hungary (4.2.4)	*Decision made and implementation agreed*: Establishment of a new system to monitor heavy rains and flash flood in a mountainous area. Installation of a new treatment plan to cope with water quality issues during floods. Shutting down of small water works in low-lying areas. Development of a regional water pipeline to increase water safety. Development of further prospective studies on measures against extreme events.	Despite the use of 3 regional climate models that yielded different results, water companies proposed to accept uncertainty and develop different adaptation measures for the future range of scenarios. Formulation of alternative management measures. Monitoring systems for climate and hydrological parameters considered as essential to deal with uncertainty.

Climate Change and Health in The Netherlands (4.2.5)	*Decision not made or not related to adaptation*: No decisions were made.	Affected how the National Environmental Agency conducts its health assessment for the Dutch Government. Led to the advice that differentiated policy approaches need to be followed according to the characteristics of both health impacts and policy options. Use of uncertainty typologies made uncertainties comparable helping to focus the appropriate policy strategies. Further use of the approach in another agency's study on climate-proofing, (for floods, water availability and urban stress).
Flood Risk in Ireland (4.2.6)	*Decision made and implementation agreed*: To approach decisions using 'softer' techniques in order to ensure robustness and flexibility.	Move from deterministic to robust and flexible approaches on the design of structural flood defences.
Coastal Flooding and Erosion in South West France (4.2.7)	*Decision made and implementation agreed*: To use a 'low regret' approach by restoring sand dunes as flood defences and relocating a road landward, instead of building dykes	Consideration of sea level rise and other drivers beyond climate change in the development of long term coastal defences. Change in local decision-makers' preferences from hard coastal infrastructure (dykes) to 'low regret' solution serving multiple functions (flood and erosion protection, biodiversity, recreation and local economy).
Québec Hydro-Electric Power (4.2.8)	*Decision made and implementation agreed*: To take into account the impacts of climate change in the planning of renovations of hydropower facilities. To review company's position and pursue further in-depth research into cost-benefit adaptation options.	Realisation that more than one climate change scenario is needed to be taken into account. Use of multiple scenarios as varying assumptions for cost-benefit analysis and assessment of the impacts of increased runoff on hydropower assets.
Austrian Federal Railways (4.2.9)	*Decision made and implementation agreed*: To improve railway track drainage in some regions taking into account a range of potential climate changes.	To move towards the climate-proofing of future investments. Realisation that the planning of new infrastructure should not focus on 'optimal' solutions but rather in a range of potential futures. To include climate change into the company's long-term strategy and enhance data collection for trend analysis and monitoring approaches.

(continued)

Table 5.3 (continued)

	Decision-Making	
Cases (Chap. 4)	Have adaptation decisions been made?	What was the influence of uncertainty management in the adaptation decision-making process?
Dresden Public Transport (4.2.10)	*Decision delayed*: Development of a model for adaptation decision-making and implementation plan for adaptation measures.	A new view on existing strategies and stimulation of actions to address associated uncertainties in relation to adaptation planning. The introduction of new methods and tools for long-term strategic planning including aiming at a future implementation plan for adaptation measures.
Hutt River Flood Management (4.2.11)	*Decision made and implementation agreed*: Inclusion of the evidence and findings into the review of flood risk management plans.	A shift in thinking from static safety and path dependency to thinking about how to build flexibility into decision making. Sharper consideration of managed retreat as an option for a low-lying area and consideration of a wider range of response options for the Hutt Valley area. Highlighted the need for a continuous consideration of changing climate risks and enabled practitioners to seriously consider complementary measures. Provided local government with a quick response scan framework suitable to be used in the discussion with elected councillors and local urban councils, on the implications of a wide range of options, costs and timings.
Communication of Large Numbers of Climate Scenarios in Dutch Climate Adaptation Workshops (4.2.12)	*Decision not made or not related to adaptation*: No decisions were made.	Improvement on the way scenarios are presented in the country. Realisation that an interactive way of presenting climate scenarios helps stakeholders to handle a larger number of scenarios and time patterns. Triggered a rethink towards the dealing with the entire range of future climate changes, possible outcomes and alternative adaptive measures.

This has also been argued for by some members of the scientific community who advocate that effective and successful adaptation planning and strategies can be developed and implemented without being significantly limited by the uncertainties present, e.g., in climate projections (Lempert et al. 2004; Hulme and Dessai 2008; Dessai et al. 2009; Lempert and Groves 2010; Walker et al. 2003; Smith et al. 2011).

In fact, Lemos and Rood (2010), go further and state that "there is an uncertainty fallacy", meaning that there seems to be a conviction that for climate projections to be used by decision-makers a reduction in uncertainty is required, which is not always the case.

In this book we looked into these issues from both a theoretical and practical perspective. We had those that need to deal with uncertainty in adaptation decision-making in mind. We believe this group includes not just the decision-makers and practitioners but also all those that support and provide them with the necessary knowledge and evidence.

The following section provides key guidance and recommendations that were extracted from the development and analysis of the twelve practical cases, complemented by the theoretical insights made available to the authors through their research and practice.

5.5 Guidance and Recommendations

Adaptation decisions are a novel area for decision-makers, practitioners and researchers alike. Dealing with uncertainty is a key element for these adaptation decisions. Uncertainty can be looked upon from three different points of view:

- It is possible to deal with uncertainties and act in spite of their existence;
- It is necessary to reduce uncertainties before making a decision on how to proceed;
- Uncertainties are considered too large and act either as a barrier to decisions or as a motive to postpone them.

All three perspectives can be found in practice as seen in Table 5.3 and in Chap. 4 descriptions of the case studies. Since adaptation options may often have associated high costs and major societal implications, the two latter views may be reasonable in particular cases. However, for the majority of adaptation situations including almost all the ones presented here (nine out of twelve cases) the first perspective appears to be the most meaningful and decision-makers do feel that despite existing uncertainties, it is possible to make climate adaptation decisions.

However, there are also cases were decision-makers feel there is a need for reducing uncertainties before investing or deciding upon adaptation measures. In this case, experience shows that (whenever possible) reducing uncertainties in model parameters through a detailed calibration procedure and/or further analysis, or improving their communication, can enhance the confidence on the evidence and make decision-makers more comfortable to act upon the results.

5.5.1 Adaptation Objectives

Setting the scene on an adaptation decision is not an easy task. The analysed cases show the current tendency towards strategic decision objectives (ten out of twelve). This confirms, to some extent, what the literature usually describes as the difficulty in moving adaptation from theory to practice. Strategic decisions are the ones associated with long-term planning and setting of goals. They are related to the development of processes and the setting up of actions (e.g. 'I want an adaptation strategy or plan for my region/city/company').

With some notable exceptions (namely the UK due to its climate change legislative framework), National Adaptation Strategies in European countries (see Chap. 3) or some of the aims proposed by the EU Adaptation Strategy (EC 2013) are examples of such strategic objectives. Instead of asserting norms and regulatory frameworks, these governance pieces seek to map a strategic perspective for decisions and actions to come.

Normative and operational objectives lie on the other extreme of available examples. These may be considered crucial for adaptation but are also harder to find in current practice. For example, in this book only three of the twelve cases describe clearly stated normative or operational objectives, with the latter being found in one single case.

This raises two questions. The first is about the transferability of results from these cases to other regions or countries in terms of uncertainty management and its influence on decisions. The second relates to the cross-analysis of what are the initially described adaptation objectives (see Table 5.2) and what are the actual operational decisions that are made (see Table 5.3).

In the first case, probably only the interested reader can provide an answer. By analysing how uncertainty was dealt in these cases, namely, the 'Water resources management in England and Wales' (normative), the 'Water supply management in Portugal' (strategic and operational) and the 'Coastal flooding and erosion in South West France' (operational), the reader will be able to judge their applicability to a different reality.

The second issue is of a different nature. What practice shows us is that, often, the primary decision-objectives are not clearly stated as being operational, exactly because there is still a lot of novelty in adaptation and because existing uncertainties do not make it easy to move towards real implementation. Nevertheless, operational decisions are being made (see the Hungarian and Austrian cases) even when the original described objective is of a strategic nature.

Uncertainty management and the confidence in the evidence and knowledge provided by support activities seem to play a role here. Changing perspectives about the role of uncertainties in adaptation decisions are a catalyst for operational decision-making even in cases were that was not originally thought of or at least not formulated in such a fashion.

A clear definition of the adaptation decision objectives and scope is recommended. This will improve communication between decision-makers and those supporting them. Ultimately it will also contribute to enhance the

communication between decision-makers and those affected by their decisions (like the public in general or relevant stakeholders).

5.5.2 Decision Support: Uncertainties, Methods and Communication

A multitude of methods and tools are available to deal with uncertainties in support of adaptation decision-making. Table 5.2 presents an overview of methods that were used in each of the case-studies analysed in this book.

All case studies addressed uncertainties related to the climate system and most addressed uncertainties related to both the climate and the human systems.

Reported uncertainties associated to the human system are mainly related with socio-economic developments, demographics and GHG emissions. Uncertainties related to attributes such as ambiguity, including the presence of multiple perceptions about what is known or probable, were not explicitly mentioned. None of the case studies explicitly addressed the (consequences of) relationships between different types of uncertainties.

Three cases reported the use of models as the single approach to support decision-making, while five reported on the use of only non-model based information for this purpose. Four of the cases reported the use of both approaches.

Regarding the direction of the approach followed in support of the decision-making process, six cases reported a top-down/predictive perspective, five a bottom-up/resilience approach and in only one case both were applied.

The correlation between the used of models and the direction of the assessments is important. Only one case used models but reported a bottom-up approach. And none of the cases that reported a top-down approach worked without models.

More than one level of uncertainty was addressed in about half of the cases. Three out of the twelve cases deliberately addressed statistical uncertainty, nine dealt with scenario uncertainty and four with recognised ignorance.

This is in line with our experience since statistical (such as probabilistic data) and recognised ignorance (such as better understanding parts of the system to each the decision is concerned) require not only a larger set of expertise but also considerable amounts of time, not always compatible with the timings decision-makers work with.

Multiple methods are applied to address uncertainty in all case studies. In the large majority of cases these include expert elicitation (ten) and stakeholder involvement (nine). In fact, seven cases applied a combination of both methods, usually in association with other methods.

By large these two methods are the most widely used in uncertainty management at the practical level. Both expert elicitation and stakeholder involvement methods rely heavily on boundary activities between those who support decisions (experts) and those making (decision-makers) or influencing them (stakeholders). This suggests that engagement between such groups is considered critical and it is actively sought out in the support of adaptation decision-making.

In fact only two cases did not report the use of any of these two methods. Interestingly, these represent two of the three cases that applied a 'model only' approach. Yet, even in these cases, meetings with decision-makers (if at an informal level without forming a 'method') to discuss uncertainty and potentially modify perspectives on the issue were mentioned, as in all of the other cases.

Nine of the selected case studies reported the use of sensitivity analysis and less commonly used methods included 'scenario analysis' (six cases) and 'probabilistic multi model ensemble' (four cases). All remaining methods were described either by one or two of the practical case studies.

These results show an interesting landscape. First and foremost a combination of multiple methods is usually applied to address uncertainty. Although it is not possible to correlate the use of methods with the decision objectives, it becomes clear that in order to support complex adaptation decision-making needs, supporting scientists or consultants tend to deploy a large number of methods to deal with uncertainties.

Only three cases used a simple combination of two methods and of those, two applied exclusively expert elicitation together with stakeholder involvement. All other cases used more than four methods in their assessments.

From our experience with these cases, the reason behind the use of such a wide variety of methods is twofold.

Firstly, researchers and others providing support to decision-making recall that, often, decision-makers are not dealing with one single or isolated adaptation decision but with multiple, sometimes even potentially conflicting ones. Furthermore, such decisions are sometimes about different geographical areas. So, in order to fit-to-purpose, the advice on uncertainties that supports multiple adaptation decisions often requires the use of multiple methods, tailored to specific objectives within the assessments.

Secondly, completeness is usually a requirement for decision-making. Having multiple methods involved in the management and communication of uncertainties can enhance the confidence in the information that is provided. This happens because the perception of the decision-maker is changed over time, by getting into contact with these methods, and maybe even being a part of them. Furthermore, methods can be complementary on a given subject and thus provide a more complete assessment of uncertainties.

The use of multiple methods to deal with and communicate uncertainties is recommended. The correct application of these methods should fit-to-purpose, cover a wide range of uncertainty typologies and aim at providing the widest range of support to different decisions and respective information needs, without compromising clarity.

The communication of uncertainties is a key element that needs to be assured not only by those supporting decision-making processes, but also by decision-makers and practitioners themselves, when addressing those affected by their adaptation decisions (general public or specific stakeholders).

Based on both theory and the analysis of the real life practices described in this book, uncertainty can (and should) be communicated in a number of ways:

- **Ensure the involvement of decision-makers and transfer of know-how throughout the development of climate risk and adaptation assessments**;
- **Guarantee that messages are clearly communicated and in a language that is common to all stakeholders involved**;
- **Promote interactive workshops in order to increase awareness of stakeholders involved**;
- **Provide guidance on how to deal with the uncertainties that are present in the outcomes of the decision-making support activity**;
- **Use visual depictions of results, including associated uncertainties. For example, the use of interactive tools for visualising scenarios allows stakeholders to handle the data as well as to continuously compare different scenarios and time steps. Other methods of providing visual depictions of results include using confidence scales and score-cards, or recurring to uncertainty typology and ranking of risks according to their likelihood and severity**.

Although the use of maps and graphs seems to be the most common approach, care should be taken since there is no one-size-fit all approach for the communication of climate change information, regardless of the country or scale of the decision.

5.5.3 Decision-Making and Its Outcomes

The twelve case studies in this book all suggest that as much information as possible should be used so as to avoid poorer adaptation decisions and to better assess the robustness of possible adaptation measures.

However, only two case studies used the information available from the web portals mentioned in Chap. 3, suggesting a need for better integration across scales and dissemination of existing information.

Since climate related uncertainties represent one more issue to consider in the decision-making process of most decision-makers and characterise only a small part of the total risks to be faced, single scenarios should be avoided as the basis of the analysis. All cases support the common notion that no such thing as a "single best scenario" exists for climate change adaptation decision-making, since single scenarios do not represent the full range of possible futures and tend to underestimate extremes.

The analysis of the practical cases has shown that conscientiously addressing uncertainty had an effect on the adaptation decision-making or at best changed attitudes towards climate change adaptation. There is often a clear shift in thinking from a deterministic or 'single optimal solution' approach to adaptation towards a flexible, robust, resilience-oriented and no-regret approach.

The suggested approaches to decision-making are numerous and should be adjusted to each decision context:

- **Prefer approaches that are robust under a wide range of possible futures, have multiple-benefits and that are low- or no-regret**;
- **Prefer options that contribute to enhance resilience and adaptive capacity**;
- **Opt for strategies that consider a wide range and variety of options and are able to support adaptive management or learning by doing approaches**;
- **Favour options and measures that allow for flexibility**.

Because of its novelty, adaptation decisions are yet to be evaluated in regard to their outcomes. Nevertheless, recent literature and several of the cases converge in the notion that monitoring and evaluation methods on one hand and favouring (to the extent possible) adaptive management approaches on the other, can offer a pathway to the future understanding of the consequences of complex adaptation decisions.

5.6 Final Remarks

Adaptation practice is a novel and dynamic field. This is reflected by an as yet limited experience in how climate change uncertainties can be best dealt with in particular situations.

As a consequence, the number of cases in this book can be, to some extent, biased towards the first steps in the development of adaptation policies and strategies (such as the assessment of risk and vulnerability). A significant range of types of decision-making objectives is likely to be underrepresented. The cases that could be included do suggest that often multi-sector and multi-scale decision-processes are covered and indicate that multiple and diverse approaches to inform decisions are applied.

Further research is required to develop methods that evaluate planned and unplanned adaptations and to locate adaptation situations in the landscape of decision-making around risk (Tompkins et al. 2010). Recent literature, mostly related to high-end climate change scenarios (i.e. above 4 °C), has called the attention to some key gaps and requirements of such high-end analysis. It has been suggested that rather than being unable to make decisions under uncertainty, what has been missing is the deployment of innovative decision-making frameworks to deal with uncertainties prompted by climate adaptation assessments (Hallegatte 2009; Smith et al. 2011).

The application of a common frame of reference in the analysis of different types of adaptation decision objectives and of the research approaches used to inform them provides a further step in the understanding of how to design and apply such novel decision-making frameworks (e.g. the role of different information needs vs. different decisions approaches).

Recognizing that site- and culture-specificity of adaptation situations makes generalized conclusions difficult, the work presented in this book aims at advancing the knowledge basis for adaptation decision-making.

By systematically collecting, selecting and analysing concrete examples where science was called upon to support real adaptation decision-making processes using uncertainty management and communication approaches, this book moves us a step closer to the better understanding of two relevant questions.

Firstly, how is science currently dealing with (and communicating) uncertainty in light of existing adaptation decision objectives and needs.

Secondly, what have been the outcomes of such approaches in terms of concrete decisions that were made (or not) and how did the use of different methodologies improve the support to those decision processes ('are better informed adaptation decisions being made?').

The guidance presented here will be subject to further development and enrichment. A growing set of concrete evidence-based adaptation decisions in a variety of situations will provide further stepping-stones towards the improvement of guidance for both decision-makers and researchers involved in climate adaptation decisions.

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Chapter 5: Discussion and Conclusions

Dealing with uncertainty is one of the central challenges for climate decision-making. The main objective of this thesis is to enrich the understanding of how adaptation (and adaptation-related) decision-making takes place in reality and how science can better support it in dealing with associated uncertainties. The motivation for this thesis originated in the practical adaptation challenges faced by researchers and decision-makers with whom I have worked with, in Portugal and in Europe, for almost a decade. This work was inspired by the need to advance the way in which uncertain scientific knowledge and policy information are combined to respond to the challenges of a changing climate. This thesis reviewed, examined and evaluated three key research questions:

- Transdisciplinarity is generally considered as being fundamental for climate adaptation research and its application to decision-making. However, is it a sufficient condition to support 'good' or 'better' real-life adaptation decision-making processes?
- What are climate adaptation decisions and how are these currently handling associated uncertainties?
- Are current adaptation decision-making frameworks well equipped to characterise and support adaptation decisions and to enhance adaptation action under uncertainty?

5.1 Decision-relevant adaptation science

The literature on climate adaptation points towards the need for the production of decision-relevant knowledge that is aligned with the requirements of the decision-makers. This has led to the adoption of transdisciplinary research as the main approach for the development of adaptation-relevant knowledge and decision-support. However, it remains to be verified if co-producing research with the actors involved (or having a stake) in the adaptation decision, is sufficient to make up for ‘good’ or ‘better’ decisions and respective outcomes. These questions reflect a perspective where adaptation research, or “adaptation science”, is expected to advance the understanding of how adaptation takes place in society, while simultaneously supporting decision-makers with their practical adaptation challenges. Chapter 2 addressed these issues by looking into how decision-relevant adaptation science is generated, developed and applied.

Transdisciplinarity can be implemented at different levels, for example, from providing information only, to consultation, and co-production (now the norm). These levels have been receiving growing attention and importance in climate adaptation decisions-making processes. The scientific discourse around climate adaptation has been evolving in the direction of one unified, practice-oriented and transdisciplinary science, which aims at informing decisions and decision-makers.

Chapter 2 defines two broad classifications of the fundamental relationships between science and the adaptation challenge. The first, termed “science for adaptation” refers to an imprecisely defined, transdisciplinary, practice-oriented form of research that aims to analyse how to address adaptation in various real-word contexts by using available theories and data to describe and advice policy practices. The second, named “science of adaptation”, describes research that aims to improve the understanding of the fundamental aspects of adaptation, by approaching it as an observable societal act that can be studied from different angles and by adopting different disciplinary perspectives. This second type requires expertise from the forefront of both natural and social disciplinary sciences.

Transdisciplinary approaches in climate adaptation research are becoming the norm, greatly because conventional disciplinary approaches have come to be considered insufficiently equipped to deal with societal requirements and the wicked nature of climate change risks. Additionally, multidisciplinary (exchange between disciplines) or interdisciplinary (integration between disciplines) approaches are now perceived as necessary but not sufficient to tackle the societally relevant problems related to climate change.

In order to understand if transdisciplinary research is indeed contributing to 'good' or 'better' adaptation decisions it is necessary to re-frame what 'adaptation decisions' are, rather than ask decision-makers what they need to make decisions. Additionally, it would require understanding how to better disentangle the types of decisions that do indeed require transdisciplinary approaches, from those that can go without them, or where they are not relevant for the decision outcome. Current literature dealing with this matter presents a wide range of perspectives that aim at supporting transdisciplinarity (McNie 2007; Pohl & Hadorn 2008; Pidgeon & Fischhoff 2011; Hanger et al. 2013; Kirchhoff et al. 2013), but further enquiry is necessary into how transdisciplinary approaches can effectively be designed and applied to climate adaptation research.

Most of the advances in adaptation research and policy originated from a natural science perspective. These were soon followed by pleas for further inclusion of social sciences in the support and conceptual definition of adaptation. Moving from the current situation where adaptation actions are typically related to 'soft' measures aimed more at improving adaptive capacity (e.g. awareness raising, capacity building, governance settings, new institutions and partnerships, information stewardship, and regulation) than at vulnerability-reducing measures, will most likely require the involvement of approaches from other fields and professionals (e.g. engineering, architecture, spatial planning, geography, policy scientists). Adaptation decision-making problems under uncertain futures will eventually require that a growing number of these disciplines are included in the assessment, appraisal and implementation of effective actions.

This is not the same as to say that adaptation requires only hard and infrastructural options to move into practice. Despite the wealth of knowledge already generated by research in the natural and social sciences realm, engineers and other professionals (e.g. involved in the development of dams, roads, bridges, buildings, drainage systems and many other infrastructures) are still using concepts and formulas with static climate variables (e.g. observed averages) and do not consider future changes and uncertainty. Therefore, at present, it would not really matter if all decision-makers facing adaptation challenges suddenly wanted to climate-change proof all the roads and other infrastructures in the world, at the lowest possible cost, unless a wide call for changed standards was set in motion, aiming at a process to develop such new standards[1]. Formulas for road design and construction are simple not yet ready to acknowledge the sort of deep uncertainties associated with climate exchange. With some relatively few exceptions, this is the

[1] During the finalization of this thesis, CEN/CENELEC started a project to work towards the integration of climate change in European standards for transport infrastructure, energy infrastructure, and buildings/construction (see http://www.cencenelec.eu/standards/Sectors/ClimateChange/Pages/default.aspx).

case in most all sort of decision-making processes involving actions to reduce vulnerability and/or increase resilience.

Transdisciplinary research may indeed be necessary to help developing a deeper understanding of climate adaptation and to improve the adaptive capacity of institutions and individuals (e.g. to support policy). However, it will probably not be sufficient to increase the understanding of practical, real-world adaptation actions such as those aiming at vulnerability-reduction options (e.g. to understand how to design a bridge using multiple scenarios of climate change and then informing the decision-maker about his/her potential choices). Transdisciplinarity may no longer be enough to advance adaptation practices. Participatory practice-oriented research is essential but needs to be complemented and connected to more fundamental scientific inquiry and technical concept development, from disciplinary sciences and focusing on other issues than adaptation. Such a move, coupled with the effective support to the creation of a “science of adaptation” (i.e. combination of research theories and methods from multiple disciplines and backgrounds) is necessary if adaptation practice is to become mainstreamed into the multiple decision-making contexts where it will be called to provide practical support.

5.2 Uncertainty and adaptation decision-making

By using a set of real-life case studies, chapter 3 addressed the research question "What are climate adaptation decisions and how are these currently handling associated uncertainties?" The selected case studies represent practical climate adaptation decision-making processes that have included the need to deal with and communicate associated uncertainties. Interviews with both decision-makers and those supporting them (i.e. scientists, consultants) allowed a better understanding of how adaptation decision-making occurs in reality.

One of the major challenges for climate adaptation research is to establish causality links between the management of climate-related uncertainties and practical real-life decision-making. While this is analysed in this thesis, the current literature on the issue is scarce, which can mean that although many adaptation decisions are being contemplated, their implementation is still lacking. A proper understanding of what constitutes an adaptation decision and how it plays out in in real-life processes is needed in order to advance a systematic evaluation of both decision-support activities and decision-making outcomes.

Most literature on decision-making under uncertainty focuses on studying and perfecting frameworks, strategies and tools (e.g. risk-assessment, precautionary principle, probabilistic data, robust decision-making, low- and no-regret options, and adaptive management). These are expected to support decision-makers in their adaptation efforts and to provide the basis for better decisions, or at least to reduce the risks associated with those decisions. Less information is available on existing efforts to map how these approaches have worked (or not), in managing uncertainty and effectively supporting different hierarchies of decisions.

Many activities are affected by climate and many decisions are made to manage its associated risks. With a changing climate, risks will also change affecting the outcome of those decisions. This will occur at the individual but also at the societal level, and may represent substantial implications for the collective well-being of human societies. However, decisions are not made instantaneously nor are they free. Decisions are known to have a 'lead time' - the time between the initial considerations about a given problem and actual implementation of the decision - and a 'consequence time' - the time over which a given decision produces effects. Adjusting (human and natural) systems and associated activities to cope with the uncertain risks posed by climate change will represent economic and societal costs. Such costs may be incurred by those promoting or suffering the adjustment, raising additional ethical challenges. Climate change poses a complex and strategic risk, because it requires decisions to be made about all sorts of policies, plans and projects expected to produce future benefits, even in a changing climate.

Willows & Connell (2003) define climate adaptation decisions, as those climate-sensitive decisions where the prospect of climate change provides the single reason for considering a decision. In other words, these decisions are directly driven by the need to manage observed or anticipated risks from climatic factors. In this type of decisions, climate change is expected to be the prime consideration in the choice between different risk-management options. Such choices are present in many areas of decision-making, which are expected to manage the consequences of climate variability associated with, e.g., cold years, flooding, droughts, storm surges, extreme wind events and heat waves. Examples include future coastal defence and fluvial flood protection, development in flood-prone areas or in other water-stressed areas, nature conservation, extreme-weather related insurance, and the management of seasonal variability in water supply.

Another type of climate-sensitive decisions, termed climate-influenced decisions, are defined as being those that may have their outcomes potentially affected by climate change, but where climate is only one amid several other factors of relevance (Willows & Connell 2003). This type of decisions may include those that are made in other areas but that can also help to explore opportunities and/or avoid the threats associated with climate change. Examples are usually associated with long-term business decisions, where climate may indirectly affect supply lines, demand for products (such as water demand) or insurance needs and values. Willows & Connell (2003) further define climate adaptation constraining decisions as those that may affect the ability of others to manage or adapt to climate change by limiting their options as it happens, for example, with inappropriate urban development in fluvial or coastal flood-prone areas.

All climate-sensitive types of decisions are potentially vulnerable to both short-term variability and extremes. However, the shorter the payback period the less vulnerable these decisions may be to the increasing climate extremes and variability currently projected. In turn, climate surprises and tipping points, i.e., large-scale events with significant consequences and low probabilities, represent risks to a wider range of decisions, but may be of particular importance to decisions with long-term payback periods.

Over- or under- consideration of climate risks relative to other non-climate risks, or a miss-consideration of the uncertainty levels in a particular decision, represent the most common cases where potential maladaptation may occur, leading to a reduction (or complete inefficiency) in the performance of a chosen adaptation option, or decreasing the ability of others to adapt in the future. Over-adaptation results when too much weight or importance is placed on the need to adapt, while under-adaptation may occur when climate adaptation is not given a sufficiently high priority (Willows & Connell 2003). Maladaptation in these cases may be related to wrongly identified options that placed too much (or too little) focus on climate change or when there is a miscalculation of the importance of other non-climate (or climate) factors in the decision. Decision-makers are expected to look for strategies that minimise the risk of making one or the other type of error.

The degree of importance of climate change in relation to other factors is difficult to characterise or quantify and is quite variable across decision types. Generically it may range from low to moderate in climate-influenced decisions to high or very high in climate adaptation decisions. Nevertheless, caution when using these concepts must be warranted, as the distinction between types of decisions is not always clear-cut and can be very context- and culture- sensitive. Practical experiences during the elaboration of this thesis reinforce this point. The precision to which a decision can be considered as being climate-influenced or climate adaptation, is extremely difficult in real-life contexts. Often, during a decision-making process, particular decisions can start as being framed as adaptation and end-up as being assessed as climate-influenced. The opposite is not as common, raising the question whether non-climate factors are being properly systematised when the objectives are defined and/or when the decision-support activities are designed.

Decision-makers such as architects, water managers, urban and other sector engineers and planners face increasing uncertainty in their activities because of climate change. Adaptation challenges may require new decision-making approaches, as current decision-support methods become increasingly hard to apply. Because of the level of uncertainty associated with climate change decisions (i.e. usually scenario uncertainty, see chapter 1), decisions-makers face the challenge of taking such outputs for their face value while adopting strategies to reduce risks. Traditionally used decisions-support tools (e.g. engineering formulations of all sorts) have been developed to function under stationary climate data (e.g. one figure for one formula, representing statistical uncertainty levels) and are, with some notable exceptions, not well-equipped to work under multiple and often contradictory inputs.

Hallegatte (2009) argues that since the climate information provided by models and observations may not be able to deliver what current decision-making processes need, then these processes require amending if they are to better deal with uncertainty. However, it remains unclear if the problem resides exactly in the overall processes (see section 5.3) or rather in the decision-making or even yet, in the adaptation decision-support activities. For example, under this perspective, it is assumed that infrastructure design needs to acknowledge a larger range of climate conditions and that this range will remain uncertain. Nevertheless, while the decision-maker may be interested in changing the way infrastructures are designed, that may not be possible because of lack of available support methodologies (e.g. building regulations, civil engineering design formulas). In order to favour robustness and enhance the consideration of uncertainty-management in the decision-making, a suit of different methods is proposed (see chapter 1). However, and although these methods may indeed be a good starting point for the development of decision-making processes that better account for uncertainty, they are not sufficient if not properly contextualised and framed within what Stafford Smith et al. (2011) argue to be a broader set of decisions types.

The work by Willows & Connell (2003), Hallegatte (2009) and Stafford Smith et al. (2011) provided a good springboard for this thesis. Extensive interviews conducted in the case studies (see chapter 2) with both decision-makers and those involved in the decision-support activities, point towards a mismatch between broad uncertainty-management approaches, as detailed in the literature, and the specific adaptation decision types that occur in real-life circumstances.

For example, when robust decision-making is chosen as the approach to be followed in a decision-making process, it remains difficult to apply because of specific technical elements. Common constraints that were reported, refer to difficulties in matching the approach with already used (and sometimes favoured) decision-support methods (e.g. cost-benefit analysis, use of worst-case scenarios as a metric), lack of baseline information to handle multiple sources of uncertainty, and the absence of available tools for incorporating the large amounts of data required to use this kind of approach. The latter is often pointed out as being incompatible with typical decision lead-times.

Many interviewees also expressed that perspectives about adaptation decision-making are slowly changing, by moving away from the search of ‘optimal’ solution towards more resilience and robustness-based approaches. However, such a change requires significant time and sufficient levels of reflectivity that are not always easy to achieve, as there are other immediate issues to deal with and multiple choices to be made, often related to non-climate drivers.

This work highlighted that not only adaptation decision lifetimes have significantly different meanings for those making the decisions (even within the same sector), but that these are often constrained by other, non-climate related organisational processes. This raises the issue whether the total lifetime of an adaptation decision is intrinsic to the type of decision or, if on the other hand, is dictated by the overall decision-making process where it is considered. For example, planning decisions about urban developments or infrastructures may be incorporated in long-term revisions of national planning regulations that only take place from time to time (i.e. every given numbers of years). In practical terms, this means that the lead-time of such decisions is often tied to these revisions, even if planners themselves are already willing to consider climate change in the planning process. In turn, this situation largely increases the time it takes for an adaptation decision to be designed and implemented. Additionally, governance and institutional settings seem to play a major role in these cases, both for public planning and for private decision-making. Overall, there is a clear need to better detail how different sorts of adaptation decisions are constrained, rather than trying to put forward a multitude of support methodologies aimed generally at supporting 'adaptation'. While these may be conceptually sound, they may also not hold for some types of decisions.

As described in chapter 1, the nature of the uncertainty in the driving factors for adaptation decisions can be described as monotonic (e.g. global mean sea level rise, global mean temperatures) or indeterminate (e.g. global precipitation patterns, increase in the number of hurricanes). While for the first type, the most important aspect is potentially the timing of expected changes, for the second even the signal of change and its effects may be uncertain. Some of the implications of the different types of uncertainty as drivers and barriers for climate decision-making have been previously discussed in the literature (see for example Dessai & Hulme 2004, Dessai et al. 2009, Dessai & Hulme 2009, Tang & Dessai 2012, Porter et al. 2014). However, analysis of their practical effects in real-life adaptation cases is largely absent until now. This is mostly because studies are usually framed from the research side and aim at advancing the usability of a given support method, approach or information dataset, rather than looking at concrete adaptation decisions.

Circumstantial evidence that decision-makers are often puzzled by contradictory signs in future climate signals, and that these may act as a *de facto* barrier for adaptation has been one of the most applied heuristics in this matter. Empirical work presented in this thesis highlights that, often in the presence of conflicting climate signals, the reason why adaptation decisions are not made (or modified versions are made for different reasons), is more related to insufficient trust in the decision-support activities, rather than in the data they produce. In turn, this further confirms the need to reject the rational view that the availability of scientific information will always translate into "good" or "better" adaptation decisions and practical actions. The implications of such conclusion for the understanding of how adaptation decisions are made in practice are wide ranging. Regarding the implications for the overall decision-making process, these are explored in section 5.3.

Adaptation takes place at many different levels of decision-making, and within a broad range of organisations. Generally speaking, decisions are sometimes described as being of a policy-, programme- or project-level type (Willows & Connell 2003). Each may have a wide range of associated objectives and in many cases, are mostly about achieving a balance across a number of different objectives. In turn, this may lead to significantly different needs and requires different types of assessment and appraisal techniques.

In this thesis, a slightly different terminology is used for the level of decision-making objectives (see chapter 3-4). Decision-objectives are divided into normative, strategic and operational. The case studies presented in this thesis, map a wide range of real-life adaptation decisions and intend to provide additional understanding of the complex interactions that shape them. The structured interviews with the decision-makers and those that supported their decisions were fundamental to better contextualise the full range of decision-making objectives and processes behind each case. By conducting a reflexive analysis of the entire range of case studies, it was possible to extract new insights into how adaptation decisions take place in reality. By discussing with those involved in the decision-making processes, such insights prove to be more than simple context-specific heuristics, opening the possibility for research to start searching for decision-type specific aspects of adaptation.

This thesis empirical results allow for a better understanding of what adaptation decisions are, how they occur in reality and how they are (successfully or not) supported by science. Firstly, it becomes clear that adaptation decisions are rarely taken outside a formal decision-making process that includes scientific or other expert support. All of those involved in the adaptation decision-making processes agree that there are many other factors playing a role in the process. For example, the initial catalyst for wanting to adapt is not always the availability of information but rather the personal or institutional perception that climate change is a problem. However, interviewees expressed that other (non-climate related) factors are generally balanced against the expert knowledge, or the climate information, underlying the adaptation problem at hand. In the cases where that information does not previously exist, decision-makers will actively support its development. There were no reported cases of adaptation decisions not using some sort of expert information although the formality of the decision-expert interface can vary significantly across specific situations. The attitudes of those involved and the level of trust that is placed on the underlying scientific (and other types of) assessments significantly affect the outcomes and the decisions that are made. Even within the same organisation, different personal values and norms place different constraints on the process. For example, knowledge that is seen as indisputable by the researchers supporting a given organisation suddenly becomes contested because of multiple views and uncertainties. Researchers and other experts are increasingly called upon to address such conflicts and are often faced with the need to generate consensus. However, it is not always straightforward for the experts to grasp the complexities of the organisational decision-making processes (or in some cases these processes are confidential) which limits the applicability of their work. In turn, this places additional challenges to the often sought-out transdisciplinarity focus of adaptation research.

Secondly, typical approaches use already existing specific standards that are usually not prepared to handle diverging futures, and thus may not hold under climate change assumptions. This means that changes in the decision-making approach (e.g. from stationarity to deep uncertainty assumptions, or from optimal to robust decision-making) generally imply making choices between different options rather than analysing different extents (e.g. height and design) of the same option. A typical example is decision-making about adaptation to flood risks. The analysis of multiple options (e.g. barriers plus urban planning changes) is usually preferred over extensive modelling of just on type of barriers (e.g. with different heights) or the assessment of multiple types of regulatory changes. Another example is water resource management where assessments usually cover the use of multiple options (e.g. additional storage capacity plus demand-management options) but typically focus on one single reservoir design and volume coupled with the use of demand-management options, rather than multiple combinations of both types and designs. Costs are usually referred to as a critical challenge in this matter. However, full-cost comparisons between using the same type of options, with different designs, and multiple types of options and designs are not generally found in the literature.

Operational decisions advance at a faster or slower pace and with more or less focus on uncertainty-management methods, depending on the perceived climate-related driver and its relation with the applicable option (or measure) design standards. An example is the decision of relocating a road or railway because of sea level rise and increasing storm surges, versus the same decision but because of perceived increase fluvial flooding or landslides. While operational standards for road design do not require sea level height or atmospheric pressure data, they do require hydrological variables to decide between changing a location and changing the type and extent of the road. Thus, the apparently same decision about infrastructural design and location can take very different forms when having to deal with questions of 'where to re-build it' and 'how to re-build it' under uncertain climate change[2]. Adaptation of other larger and less flexible hard infrastructures such as dams and water transport and distribution systems are seemingly better equipped to manage multiple climate uncertainty-management analysis and support activities.

[2] For interesting discussions on the topic see the US Infrastructure and Climate Network (ICNet) notes available at https://www.unh.edu/erg/sites/www.unh.edu.erg/files/jacobs_eos_2013_1.pdf and http://theicnet.org/wp-content/uploads/2015/08/Outreach-Synopsis.pdf

Operational design standards for dams and water systems always have to consider climate-related variables and extremes (unlike a road). However, relocation of these infrastructures is much harder and with substantially longer lead-times, which increases the complexity of the decision. Deciding to retrofit or change the operational procedures of these structures can become a very long-term cycle of assessment and support even when decision-makers are already convinced of the need to adapt. Operational decision-making is usually associated with existing standards and norms (engineering methods, optimisation, and cost-management) and decision-makers can become sceptical when having to handle combinations of this type of decisions, with soft changes such as the ones typically associated with institutional strengthening, awareness raising and capacity building.

Strategic decision-making on the other hand is familiar with long lead-times, multiple assessments and consensus building. Strategic adaptation decision-making is often about pausing and reflecting before acting or changing processes. Nevertheless, it is extremely difficult to imagine a perfectly defined adaptation decision, i.e. one that is only operational or strategic in its nature. So, in practice, decision-making processes tend to bundle several types of adaptation decisions and thus need decisions frameworks that recognise this and provide support accordingly, e.g., by allowing multiple uncertainty-management methods to be simultaneously deployed. Strategic decision-making often precedes operational decisions, but as seen above, they are not necessarily completely inter-dependent in their approaches.

Finally, the nature and type of the adaptation decisions plays a key role in determining the desirable amount, type, and communication formats of scientific data used in the process. As expected, large national and multi-sector strategic decisions rely on broader methods with coarser detail. Small scale, local operational interventions look for more fine-detail, tailored information. However, both types of decisions may struggle with both the quantity and the format of the available data. For example, large ensembles of climate model data are difficult to use regardless of their scale and associated uncertainties. Considering multiple scenarios may be constrained by the costs and complexity of the required modelling. These aspects need to be considered when framing an adaptation decision and, most importantly, when designing and implementing decision-support activities, such as using uncertainty-management methods and tools.

The points presented in this section aimed at enhancing the understanding of how adaptation decisions under uncertainty play out in reality. However, they are also related to (if not imply) the need of developing new decision-making frameworks for climate adaptation. The different types of adaptation decisions that were assessed can often be at odds with frameworks that have in mind the development and improvement of decision-support methods and approaches. Fully integrative adaptation decision-making frameworks should consider the objectives/types of adaptation decisions and the nature/types of uncertainties underlying those decisions. The following section considers and discusses these matters from a framework development perspective.

5.3 New adaptation decision-making frameworks

The empirical work presented in chapter 3 was analysed in chapter 4 to provide for a synthesis of both theoretical and practical elements of climate adaptation decision-making under uncertainty. A general framework was developed to provide a common frame of reference to this analysis and to allow for the extraction of comparable lessons from practice.

While chapter 3 dealt with understanding how adaptation decisions are made in real-life practical examples, chapter 4 addressed the question "Are current adaptation decision-making frameworks well equipped to characterise and support adaptation decisions and to enhance adaptation action under uncertainty?"

Results point toward the conclusion that current frameworks for adaptation decision-making under uncertainty come from a research perspective, address strategic rather than operational decisions, and do not properly account for learning, as this section will elaborate.

They represent the development of numerous analytical approaches that are expected to support adaptation decision-making in dealing with uncertainty. These analysis frameworks focus on the synthesis of available information across many segments of the climate change challenge in order to assist decision-makers in assessing the consequences of their adaptation choices. These dimensions have been so far dealt separately in literature and in practice. Transdisciplinarity research has been proposed as a way of bridging this gap, but as demonstrated above, may not be sufficient or completely effective in moving adaptation into practice.

Current state-of-the-art suggest that a growing understanding of the aspects of decision-making and the development of uncertainty-management approaches, methods and tools has led to improved climate adaptation decisions and practical decision-support. While this may be true for some particular cases, this thesis argues that the current separation between the analysis of what are adaptation decisions, on one hand, and the support decision-makers need to improve them, on the other, is no longer sufficient.

Despite the wide range of definitions, the adaptation and decision-making literature typically describes decision-making processes as cycles consisting of four stages namely, scoping, analysis, implementation and review. Most research efforts have been place in the first two stages, with implementation and review receiving less attention. While the same critic may be pointed to the this thesis, this further reinforces the already discussed notion that practical adaptation decisions (especially those aimed at reducing vulnerabilities) are not evolving at the expected rate, or there would be more to implement and review (or monitor).

A second issue with the current framing of adaptation decision-making processes is that it has been looked upon using research lenses, which have compartmentalised the way decisions and decision-support approaches are described. As shown in chapter 1 a great deal of effort has been placed in understanding the needs of decision-makers (e.g. information, data, and communication) and developing broad sets of criteria and analytical approaches to support their adaptation decisions.

Additionally, research framings for each one of these two areas (or "compartments" of a decision-making process) have further divided what should be integrated. With some notable exceptions, contextualising the fundamental aspects of adaptation decision-making has been the focus of social sciences, while the development of decision-support and uncertainty-management methods has continued to receive more attention from the natural sciences. Again, transdisciplinarity research has been called upon to bridge such a divide, under the assumption that having a multi-disciplinary perspective coupled with the engagement of those involved in making the decisions, would lead to enhanced decision-making processes.

There have been some notable attempts to generate guidance that cuts across these steps and provides help to both decisions-makers and researchers. A widely used example is the risk-assessment framework by Willows & Connell (2003) and sub-sequential revisions by Ranger et al. (2010) and by the UKCIP (UKCIP 2013). Further adoption of these UK-based frameworks and guidance by many organisations and countries[3], interested in advancing their levels of practical adaptation action, suggests a growing interest towards decision-focused and integrated approaches.

In order to help suppress the identified challenges of assessing climate adaptation decision-making under uncertainty, this thesis proposed that new decision-making frameworks might be necessary. It is suggested that instead of new methods and tools, what is required is a better understanding of how different types of decisions are currently being made (or not) and how they are (or not) influenced by current available knowledge and support activities. Since a changing climate is expected to affect the outcomes of a wide range of decisions, new decisions-making frameworks

[3] Examples include the Adaptation Support Tool made available through the European Climate-ADAPT platform (http://climate-adapt.eea.europa.eu/) and applications across such diverse countries as Australia, Brazil, China, Germany, Portugal and New Zealand.

should be able to map out and integrate across the different stages of the adaptation decision-making processes.

The generic adaptation decision-making framework introduced in chapter 4 consists of four interconnected dimensions representing the key stages that are typically described for a decision-making processes. The idea was not to break away from current developments in adaptation, policy and decision research but rather to help advance the understanding of how available uncertainty-management and decision-support activities can be connect to real-life typologies of adaptation decisions.

The first dimension of the framework deals with the decision-objectives. These are closely associated with the types of adaptation decisions discussed above. The second dimension is related to decision-support activities, e.g., assessments and science based methods and tools. This dimension includes the use of models in the support activities, the type and direction of the approach followed in the assessments and the primary level of uncertainty dealt with by the decision-support activities. The final two dimensions are relative to the actual adaptation decisions and their (prospective) outcomes. The framework was applied in the (desk) analysis of the case studies and complemented by interviews with both the decisions-makers and the experts supporting each case.

Each case study was analysed in relation to first three dimensions of the framework. First, the primary decision objectives were assessed, according to the information provided by the decision-makers. Secondly, the set of decision-support activities carried out in each case was described and discussed with the responsible experts. Finally, the adaptation decisions were mapped out to provide a clearer understanding of what was decided, and which choices were actually made (or not, and why not). The final dimension, representing the outcomes of the decision, was not fully assessed in this work because it was considered as being premature at this stage, and thus not lending itself to a proper appraisal. However, recent literature has pointed out multiple approaches, methods and tools to enhance the monitoring and evaluation perspective of climate adaptation (see Bours et al. 2013, Dinshaw et al. 2014, OECD 2015). It is expected that, over the coming years and decades, these approaches are able to help in the evaluation of the adaptation decision-outcomes. A recent and emerging discussion with significant importance for this dimension, is related to the notion of continuous cycles of reflection, learning and reframing of objectives in accordance to the decision-making contexts (see Berkhout et al. 2006, de Boer et al. 2010, Berkhout et al. 2013, Baird et al. 2014, OECD 2015).

Regarding the first dimension of the framework (i.e. objectives), results confirm that most adaptation decision-making processes are currently dealing with strategic or process-oriented changes. Only two of the cases dealt with operational or action-oriented adaptation decision, which in turn seems to reflect that adaptation is still very much oriented towards building adaptive capacity and not so much vulnerability-reducing actions. This is reinforced by the literature, but also by the set of case studies that were analysed, but not included in chapter 3, and by the author's own knowledge of other cases in Europe and elsewhere. Additionally, normative or regulatory decisions were found in only one case. This was further confirmed by the interviews with decision-makers. Most respondents do acknowledge the difficulty in moving towards operational and practical decisions, of the sort commonly associated with technical design standards. Several reasons have already been pointed out, but it is important to stress the role of uncertainty in this matter. A significant number of involved decision-makers pointed out that the problem was not associated with the climate information itself, but rather the way existing frameworks are unable to deal with that uncertainty (e.g. by trying to apply multiple diverging scenarios to process and formulations that were developed to deal with single values and stationarity, while asking for the decision-maker needs).

The second dimension of the framework (e.g. support) is divided in three major components, namely the use of models in the support, the direction of the assessment approach, and the uncertainty levels that are dealt with.

The first deals with the use of models in support of adaptation decisions. These can be numerical or non-computer based. Mental models were not considered in this thesis. Current climate change related research devotes quite some attention to model-based approaches. These serve to enhance the understanding and assessment of potential changes in climate and other systems, as well as its implications in terms of impacts, vulnerability and responses (i.e. adaptation but also mitigation). The effects of the use of this sort of models both in research and in decision-support are wide ranging and beyond the scope of this thesis. However, because models play a significant role in informing decisions, but are also responsible for increasing or adding further uncertainties, they should be considered in the analysis of any adaptation decision-making processes. The analysis of the case studies points towards a growing importance of non-model approaches such as the use of expert elicitation and stakeholder involvement. This is in line with the emergence of transdisciplinary adaptation research as discussed in chapter 2. However, context specificities relative to the availability of the knowledge and resources necessary to use models can play a significate role here. All cases are from developed countries, and even within these significant disparities are observed in the level of climate related research (e.g. number of experts, availability of data). This warrants caution in the extrapolation of conclusions about the use of models in support of adaptation decision-making. Therefore, comparative studies within the same country, and if possible within a large number of countries, would be desirable.

The second component is relative to the direction of the approach applied in the decision-support activities. Top-down approaches are related to a more classical optimisation or “science-first” perspective, while bottom-up approaches are grounded in robustness, resilience or “decision-first” applications. The case studies do not show a clear trend towards either of these approaches. These results do not confirm the expected shift towards a more bottom-up perspective, which is often described in the literature. Interviews and other experiences with adaptation experts supporting decision-making processes reinforce this idea. Decision-makers still seem to rely heavily on top-down assessments and on climate and impacts information, partly because they are still very much in a phase of growing awareness and risk assessment.

The third and final component is the level of uncertainty addressed by the decision-support activities. As discussed in chapter 1, the concept of uncertainty levels is not a straightforward one. Nevertheless, it plays a major role in the choice and application of different methods and tools, even if not always in a conscientious form. Several of the interviewees (both decision-makers and experts) acknowledged that no formal definition or systematic consideration of uncertainty (at least as described in the literature) played any sort of initial or significant role in the decision-making process. Only after concepts and definitions were clarified did the involved actors realise the levels and nature of uncertainty they were dealing with. After that, almost all considered it very useful to understand the academic concepts, as they could recognise them in the practical discussions. There is a clear tendency for the use of methods and tools that provide management at the level of scenario uncertainty (see chapter 1). In this regard, the interviews clearly pointed out to a connection between the resources available and the expertise of the researchers (and other experts) supporting decisions, and the level of uncertainty that is addressed. In other words, what seems to drive the uncertainty assessment and choice of management methods is the approach preferred by the experts, rather than the perspective or the needs of the decision-makers. This seems to hold even under growing levels of transdisciplinarity and research co-production.

Because of the reasons stated above, and since there is a recognised lack of practical advances in real-life adaptation action, it becomes apparent that current decision-making frameworks that look into the adaptation decision-making processes from a compartmentalised perspective, need to be replaced with others of a more integrative nature. New frameworks need to be flexible and accommodate the multiple "schools of thought" that are currently available regarding uncertainty management. They need to be reflexive and allow the use of multiple uncertainty-management methods and tools that reflect the wide range of decision-objectives that naturally occur in real-life. Finally, they need to recognise the role of different actors (decision-makers and experts) within the adaptation decision-making processes, and most importantly, the implication they have for different adaptation decisions.

A final note to acknowledge that the perspective of this thesis reflects the insights gained through the empirical work with the case studies, but also the author's experience in working with practitioners and decision-makers at the EU-level, in Portugal and from other European countries. While the classifications presented in this thesis are expected to cover a wide range of adaptation decisions, they reflect the context of developed countries. Contexts for planned adaptation in developing countries may differ significantly, in relation to both types of decisions objectives and availability of decision-support.

5.4 Reflections, research gaps and next steps

Climate adaptation decision-making under uncertainty is not a simple matter of choosing a single approach, method or tool and applying it. Rather, multiple decision objectives and multiple roles and perspectives that shape the decision-support activities are required to handle multiple levels of uncertainty, for a diverse set of decisions.

Adaptation as a decision-making process needs to consider not just climate-related but also non-climate related uncertainties. This requires disciplinary sciences from both natural and social perspective to be interested and engaged in climate adaptation research. Climate adaptation decision-making processes should avoid "magic numbers", as presented by Funtowicz & Ravetz (1990) and "magic concepts", as pointed out by Pollitt & Hupe (2011), unless they are geared towards forging agreements and helping to raise awareness. Motivational factors around such an approach can play a significant role, and further research into how to include their generation and use within adaptation decision-making frameworks is welcomed.

Climate adaptation research and decision-support activities should not be transformed into a brokering platform for handling conflicting values and opposing views under the risk of turning into a negotiation forum and loosing scientific quality and salience. This is however a real possibility as growing support for deliberative democracy processes, at least in western-world contexts, can indeed start to mix up what are adaptation decisions requiring a technical support and what are the means and processes to achieve policy consensus. Research into how policy and consensus generating approaches can help to connect further the different dimensions of the decision-framework should be promoted.

Adaptation science should have a balanced combination of "science for adaptation" and "science of adaptation". Striking such a balance is likely to increase the societal impacts and enhance the current dominant focus on practice-oriented science, which may lead to a multitude of case studies without necessarily a better understanding of the underlying processes or the development of frameworks and methodologies that really work. Disciplinary research that assess how operational design standards need to change, across a wide sorting of decisions, multiple sectors and cultural settings is desirable. A proper connection of its results to policy and governance processes and transdisciplinary-focused research may help to advance the current observed levels of practical adaptation action.

The findings of this thesis point towards the need for further research in a number of important areas. Firstly, the development of systematic methods for a consistent tracking of adaptation practices, in particular those related to vulnerability-reducing actions. Secondly, research is required into the interactions that occur within and between each dimension of the adaptation decision-making framework, in order to allow for a broader understanding of the respective implications for real-world adaptation actions. Thirdly, the development of comparative analysis in developing countries is necessary to allow for an expansion of the generic framework into other contexts and to appraise its universal application to adaptation decision-making under uncertainty. Finally, research is required to advance the understanding of what are the types of decisions where transdisciplinarity is fundamental, those where it is relevant but not critical, and those where what is lacking is rather a disciplinary approach to the way decision-making needs to change to better adapt under a changing climate.

5.5 References

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