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DET NORSKE VIDENSKAPS-AKADEMI

Extreme Weather Events in Europe: preparing for climate change adaptation

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Summary of present knowledge and ongoing research: Professor Christos Zerefos wrote on the principal extreme weather phenomena in Mediterranean/Southern Europe; Professor Trond Iversen, Professor Nils Gunnar Kvamstø and Dr Rasmus Benestad were responsible for the section on changes in extreme precipitation in Northern Europe; Dr Erich Fischer wrote on droughts and temperatures; Professor Daniela Rezacova was responsible for the discussion of convective events and heavy rain storms/wind storms; Professor Ulrich Cubasch, Professor Uwe Ulbrich, Dr Gregor C. Leckebusch, Dr Markus Donat wrote on large-scale wind storms; Professor Zbigniew W. Kundzewicz contributed with discussion on intense precipitation and floods; Professor Peter Höppe discussed natural catastrophes in Europe – trends of loss-relevant extreme weather events – and Professor David Rios provided material on statistics and risk analysis in the characterisation of extreme weather. The contributions were then assembled into one assessment by Dr Rasmus Benestad, Professor Øystein Hov and Professor John Murlis.

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PREFACE

This study arises from the concern that changes in weather patterns will be one of the principal effects of climate change and with these will come extreme weather. This is of considerable consequence in Europe as it impacts on the vulnerability of communities across the continent and exposes them to environmental risks.

It is now widely recognised that failures in international efforts to agree on the action necessary to limit global climate change mean that adaptation to its consequences is necessary and unavoidable (Solomon *et al.*, 2007). The changes anticipated in the occurrence and character of extreme weather events are, in many cases, the dominant factor in designing adaptation measures.

Policy communities within the EU have begun to consider appropriate responses to these changes and an EU adaptation strategy is under active development and implementation. There are also sectoral EU initiatives, for example on water shortages and heat waves, and, at a regional level, on planning for floods and storms.

The basic and unavoidable challenge for decision makers is to find workable and cost-effective solutions when faced with increased probabilities of very costly adverse impacts. Information about the nature and scale of these changes is essential to guide decisions on appropriate solutions.

Agenda-setting for climate change and adaptation has to take place in a social or/and political setting. Scientific information about temporal changes in the probability distributions of extreme weather events over Europe, the main focus of this report, is important for informing the social and political processes that it is hoped will lead to adequate climate-change adaptation measures in Europe.

This report is focused on providing a working-level assessment of the current state of the quantitative understanding of relevant extreme weather phenomena and their impacts.

Given the current state of scientific knowledge and the requirement to deliver a timely input to policy processes, the scope of this report is inevitably limited and it does not set out to provide a comprehensive coverage of all extreme weather phenomena and impacts in the EU. However, there are crucial aspects of additional risk and uncertainty from extreme weather that are highly relevant to the work of EU policy makers and we aim to cover them in this report.

The report has been prepared by a Working Group sponsored by the Norwegian Academy of Science and Letters under the chairmanship of Professor Øystein Hov. EASAC has collaborated on this work and published a condensed version of the report as part of its work on climate change and public policy issues which can be found on www.easac.eu.

The objective of the present document is to provide a handy tool for policy makers to whom the background science may not be immediately accessible. The report starts with a description of the way in which extreme weather phenomena are characterised, in particular through the use of statistics. Subsequent chapters then describe the state of knowledge about the key extreme weather phenomena, the impacts they have and some of the broad approaches that have been taken, within sectors and at different geographic scales, to reduce these impacts through adaptation measures. In a final chapter we consider the particular case of adaptation within European agriculture. The report concludes with a summary of major findings and some broad recommendations for strengthening the information available for decision makers in Europe.

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EXECUTIVE SUMMARY

The current position:
recent changes in extreme weather patterns

1. The Earth's climate has changed in the past due to geophysical factors, including the oscillation of its axis as it travels round the sun. Over recent years, however, human activity has been the cause of more profound and rapid change. Since the industrial and agricultural revolutions, the use of fossil fuels as energy sources, together with intensive agriculture and deforestation, have led to an increase in atmospheric carbon dioxide (CO_2) and methane (CH_4) levels which are now higher than at any time in the last 800 000 years. This will have a profound effect on the Earth's climate, which will warm as a result.

2. Meteorological and climatological measurements of climatic change in Europe show that intense precipitation has become more severe and more frequent, with complex variability in the sense of a non-uniform spatial pattern. However, the lack of a clear large-scale pattern can be expected when dealing with extremes, as the number of events is small and they take place at irregular intervals and with irregular intensity.

3. Winter rainfall has decreased over Southern Europe and the Middle East, and has increased further north. The latter increase is caused by a pole-ward shift of the North Atlantic storm track and a weakening of the Mediterranean storm track. Short and isolated rain events have been regrouped into prolonged wet spells.

4. Some recent changes in the pattern of weather extremes have been considerable: in some parts of Europe, observed trends to more and longer heat waves and fewer extremely cold days and nights have been observed. Since the 1960s, the mean heat wave intensity, length and number across the Eastern Mediterranean region have increased by a factor of five or more. These findings suggest that the heat wave characteristics in this region have increased at higher rates than previously reported (Kuglitsch *et al.*, 2010).

5. Increasing summer dryness has been observed in Central and Southern Europe since the 1950s, but no consistent trend is found over the rest of Europe. In a study of river flows in Europe by Stahl *et al.* (2010), a regionally coherent picture of annual stream-flow trends emerged, with negative trends in southern and eastern regions, and generally positive trends elsewhere – especially in northern latitudes – suggesting that the observed dryness is reflected in the state of rivers.

6. The risk of and vulnerability to floods have increased over many areas in Europe, due to a range of climatic and non-climatic impacts, whose relative importance is site-specific. Flood damage has increased substantially, however observations alone do not provide conclusive and general proof as to how climate change affects flood frequency. An ubiquitous increase in flood maxima is not evident.

7. The insurance industry reports a pronounced increase in the number of weather-related events, which have caused significant losses, for example, wind-storms and floods globally and, to a somewhat lesser degree, in Europe. There is still insufficient knowledge about the extent to which these changes can be found in wind and precipitation observations and whether they are driven by global warming. Some of the hazard-driven increases of loss events may have been masked by human prevention measures, in particular in the case of flood loss data, as these can be influenced much more by preventive measures than wind-storm losses.

8. In some regions, low-lying coastal zones are considered to be particularly vulnerable to climate change, especially through sea-level rise, changes in wave climate and in storminess. In Portugal, one of the European countries most affected by coastal erosion, the shoreline is retreating at an annual average of as much as 9 m in places, mainly as a result of weakening of river sediment supplies due to dams and embankments. However, the question of past trends in storm number and intensities is still open. More North European wind storms are seen when the state of the North Atlantic Oscillation (NAO) is in a positive phase, but the causes determining the phase of the NAO are still unclear.

The outlook

1. The main tool for providing insights into possible climate futures is computer modelling. Using modelling studies with other inputs, some of the likely trends for the future can be seen. In particular, a consensus is emerging about the likely future pattern of extreme weather events in Europe. Heat waves are very likely to become more frequent, with increased duration and intensity, while the number of cold spells and frost days are likely to decrease. Fewer cold extremes are expected, but occasional intense cold spells will still occur, even in the second half of the 21st century. Southern Europe and the Mediterranean Region may expect a combination of a reduction in annual precipitation and an increase in average temperatures. Summer dryness is expected to further increase in Central and Southern Europe during the 21st century, leading to an enhanced risk of drought, longer dry spells, and larger soil moisture deficits.

2. Climate model simulations also suggest more frequent droughts throughout Europe, although flash and urban floods triggered by local intense precipitation events are also likely to be more frequent. Other likely consequences of climate change include decreased annual river flow in Southern Europe and increased water stress in regions that are already vulnerable to reductions in water resources.

3. Studies suggest higher precipitation intensity for Northern Europe and increased dry-spell lengths for Southern Europe. High intensity and extreme precipitation are expected to become more frequent within the next 70 years. The increased frequency is estimated to be larger for more extreme events, but will vary considerably from region to region. The seasonality and structure of precipitation is expected to change.

4. It is currently not possible to devise a scientifically sound procedure for redefining design floods used, for example, in planning for food defence (for example, 100-year floods) due to the large range of possible outcomes. For now, adjusting design floods using a climate-change factor is recommended, but flood-risk reduction strategies should be reviewed on regular basis, taking new information into account.

5. Climate model simulations indicate an increase in wind-storm risk over Northwestern Europe, leading to higher storm damage when there is no adaptation. Over Southern Europe, severe wind storms are projected to decline.

Economic impacts of extreme weather events

1. Much of the information about the economic impacts of extreme weather events comes from data on insured losses compiled by the insurance industry such as that held by the Munich Re company in its NatCatSERVICE, comprising about 30 000 data sets of individual loss events caused by natural hazards. This analysis shows that, in general, the frequency of weather-related loss events has increased significantly at a global level, in contrast with losses from geophysical hazards such as earthquakes or tsunamis, which have shown only a slight increase.

2. In Europe the increase in losses from extreme weather events has been about 60 % since the 1980s. This is low compared with the number of loss events suffered in other continents, which, in the case of North America, are now 3.5 times the number of the early 1980s. Of the loss events registered in the NatCatSERVICE database, the great majority, 91 %, are from extreme weather and, of these, 75 % are from storms and floods.

3. The pattern of loss events varies across Europe, with larger numbers in the United Kingdom and West-Central Europe and lower numbers in Scandinavia and Northern Europe. In Southern Europe, heat waves, droughts and wildfires are the most numerous events, whereas in Western and Central Europe floods and storms predominate.

4. The economic loss burden has been considerable, with an estimated loss of € 415 billion (€ 415×10^9) since 1980 (2010 values). The most costly hazards have been storms and floods, amounting to a combined total of almost € 300 billion.

5. Weather events have also been responsible for considerable loss of life in Europe, estimated at around 140 000 lives lost since 1980. The largest impacts on life have come from heat waves such as those in Central Europe in 2003.

Adaptation strategies: responses to changes in extreme weather

1. At the European level, climate-change adaptation is part of the strategies for improving the resilience of specific sectors, such as health and transport, reflecting the expected impacts of climate change on them. It is expected that the severity of climate change will be greatest in the Southern and Mediterranean parts of Europe and that there will be particular problems in some specific geographical areas including mountain areas,

coastal zones and islands. Agriculture, fisheries, human health, water resources, biodiversity and ecosystems and physical infrastructure, including transport and energy are expected to be particularly affected.

2. Much of the adaptation action required in the EU will be carried out by individual Member States. The European Environment Agency (EEA) is collaborating with the European Commission (EC) to establish a European climate adaptation platform (Climate-Adapt), which aims to support Member States in the development of National Climate Change Adaptation Plans.

3. Some adaptation measures will require action at a European level, including where there are shared resources such as sea-basins and rivers or geographic features such as mountain ranges that cross national borders. There will also be a particular requirement for EU action where sectors or resources have strong EU integration, for example, agriculture and fisheries; water, biodiversity and transport; and energy networks.

4. For many of the adaptation measures that will require EU-level action, some are sector-specific requiring the general improvement of storm resilience in electricity networks. Some have regional and cross-sectoral implications such as flood-risk management along the courses of the great rivers of Europe with implications for agriculture and for physical infrastructure.

5. The current EU strategy rests on information sharing and integrating adaptation into EU policies.

Conclusions

1. A regional European pattern in recent trends in extreme weather and their impacts has been discerned. Some of the extreme weather phenomena associated with climate change are increasing in frequency and intensity within Europe. In some cases the impacts of these changes have had a significant effect on societies and economies throughout Europe, although at very different scales in different regions.

2. There is an observed trend to more and longer heat waves and fewer extremely cold days and nights in some parts of Europe. In the past, estimates of changes have suggested that they are modest, but a recent re-analysis of data showed that, since the 1960s, the mean heat-wave intensity, length and number across the Eastern Mediterranean region had increased by a factor of five or more (Box 3.1). It is expected that the trends towards longer and more intense heat waves will continue with further climate change.

3. Increasing summer dryness, which is associated with drought, has been observed in Central and Southern Europe since the 1950s, but no consistent trend has been found over the rest of Europe. For some areas, notably Central and Southern Europe and parts of Northwestern Europe, it is expected that this trend will continue with global warming.

4. Extreme precipitation, often associated with floods and damage to infrastructure and crops, appears to be increasing in severity and frequency.

5. Climatic and non-climatic factors such as human settlement have increased flood-risk vulnerability over many areas. Flood damage and the number of large floods have increased substantially in Europe, however a ubiquitous increase in observed records of annual flood maxima is not evident.

6. Projections for the future indicate increases in flood risk over much of Europe. However, the projections are uncertain, partly because information about the future evolution of precipitation is uncertain but also because of confounding non-climatic factors.

7. The question of past trends in storm numbers and intensities is still open. More North European wind storms are seen when the state of the NAO is in a positive phase, but the causes that determine the phase of the NAO are still unclear.

8. In some regions, low-lying coastal zones are considered to be particularly vulnerable to climate change, especially through sea level rise, changes in wave climate and in storminess.

9. Insurance industry data clearly show that the number of loss-relevant weather extremes has increased significantly globally and to a smaller, but still relevant, degree in Europe. There is increasing evidence that at least part of these increases is driven by global warming. Some of the hazard-driven increases in loss events may even have been moderated by human activities through loss prevention measures.

10. Human factors play a part in moderating the impacts of heat waves. Extreme heat has had a considerable impact on human health in Europe with significant mortality, notably during the heat waves of 2003 and 2010. However, in many parts of Southern Europe, heat waves of a similar scale occur frequently for years without the same level of impact.

11. For many crops in Europe, weather extremes are the major factor in climate-change impacts on production. An increased frequency of extreme weather events is likely to be unfavourable for crop production, horticulture and forestry.

Recommendations

It is recommended that science-driven climate services need to be developed on national and regional levels in Europe. As the societal risk related to climate change is significant, research into the processes and drivers of the climate system need to intensify, with a particular emphasis on manifestations that carry the largest risk to humans and society. These manifestations are related to the extremes of the weather-parameter probability distributions, rather than on their mean.

Climate services should evolve in an interactive way with the public and private user communities in order to devise effective adaptation measures and to:

- provide easy access to relevant meteorological and hydrological observations, climate projections and climate products, with climate adaptation as the main focus;
- facilitate the production of clear information about national/regional climate;
- provide updated information on historical, current and future climate trends;
- facilitate and disseminate relevant quality-controlled analyses of the present climate and projections of climate change to governments, counties, municipalities, business interests and research.

When there are events that focus attention on impacts of extreme weather events, individual efforts to assimilate the lessons learned into planning should be encouraged. The use of real-world indicators, such as recurring problematic conditions and external expertise where municipalities or organisations are involved in relevant research projects, should also be encouraged as ways of raising the local profile of climate-change adaptation.

CHAPTER 1 INTRODUCTION

1.1 Knowns and unknowns associated with adaptation to climate change

Extreme weather can have a severe impact on society. For example, during the summer of 2007, the United Kingdom experienced a series of destructive floods across the country; there is a long history of flood-risk management in the United Kingdom, but the severity of the 2007 floods was such that defences were overwhelmed. Eastern Europe and Russia experienced unprecedented heat waves during the summer of 2010, with blazing wildfires. The analysis of risk, the product of the probability of extreme weather and the severity of its consequences, is an essential tool in managing impacts on society. In this analysis, the quality of the information available about the future of extreme weather is crucial.

All questions associated with climate change involve some kind of calculation of future conditions. Although many of the factors that go into such calculations are well understood and characterised, there are numerous unknowns and different calculations will span (and represent) a range of different possible scenarios. It has sometimes been a challenge to communicate the consequences of this range of possibilities to decision makers, and it is therefore important in this work to highlight the knowns and the unknowns and assess how these affect the predicted outcomes. For example, a recent model-based analysis carried out by Deser *et al.* (2012) suggests that large-scale atmospheric flows may dominate local and regional climates even on 50-year time scales, and potential outcomes for a location may range from hardly any warming to very rapid temperature increases. Furthermore, some outcomes may be more likely than others, so that the range of plausible future conditions should be described by a probability distribution. This report follows the guidelines outlined in the Intergovernmental Panel on Climate Change's *Good Practice Guidance Paper on Assessing and Combining Multi Model Climate Projections* (IPCC, 2010).

There is climate information with high precision for past climatic conditions and trends, from which it is possible to deduce a number of trends and interrelationships. Sometimes the observational data are lacking, but it may still be possible to infer useful local information from related locations and inter-dependencies. In the global climate system, different processes are interconnected through the laws of physics. The dependencies between different aspects of our climate systems and their past evolution can be studied through numerical model simulations and distilled through the use of mathematics and statistics, providing information about both the processes themselves and the quality of our information.

There is also high-precision information on how weather phenomena have affected society in terms of damage and opportunities, and hence the link to the local climate, which describes the typical weather pattern as well as the frequency of extremes.

The models used for calculation of future climate conditions consist of large volumes of computer codes which solve equations describing the Earth's climate system as a set of interacting physical processes. They describe the energy, mass, and motion in the atmosphere and oceans, which are relatively well understood and characterised, but also need to accommodate some physical aspects of the climate system which are known to a lower precision.

Aspects known at lower precision levels typically include processes which take place on small scales, such as the exchange of water and energy between the land surface and the atmosphere, snow and ice, the behaviour of cloud drops, interaction between light and gases/particles, and the effect of pollution. Climate models are large in computational terms and therefore require high efficiency. They need to solve complex equations quickly and do this by using approximations where these can be justified by the physics of the processes concerned.

Furthermore, climate models need information about future greenhouse gas concentrations, land use and solar activity. This information must be based on assumptions about future human activity and the shape of future society, derived from scenario storylines. Hence, the future values for meteorological parameters do not correspond to the type of prediction that is normally presented in daily weather forecasts, but are conditional on assumptions about the future that may vary considerably according to the scenario on which they are based.

1.2 Recent developments in the study of extreme weather and the effect climate change will have on it

In the period 2001–2005, three EU research projects were commissioned under the EU's Fifth Framework Programme on the study and modelling of climate and weather extremes. These were the Modelling Impact of Climate Extremes (MICE[1]), Statistical and Regional Dynamical Downscaling of Extremes for European regions (STARDEX[2]) and Prediction of Regional scenarios and Uncertainties for Defining European Climate change risks and Effects (PRUDENCE[3]).

The key messages from MICE[4] were about the processes of analysis and projection. The conclusions were that, at the time of the report (2005):

- it was difficult to distinguish between natural variability and climate change;
- climate models had limitations and uncertainties;
- climate models were the best tools available for long-term climate prediction;
- climate models would be needed to build regional scenarios of climate change;
- such scenarios would be the basis for studying the impacts of climate change.

The conclusions from STARDEX[5], on the other hand, were focused on the outcomes of modelling. They were that:

- there had been changes in European temperature and rainfall extremes over the past 40 years and future projections indicated major changes to come;
- there were uncertainties in regional scenarios of extremes, associated with the methods used to downscale future projections to the spatial scales required for many impacts assessments;
- it would be necessary, therefore, to take a multi-model approach to regional scenario construction, whether using statistical and/or dynamical downscaling methods.

The PRUDENCE project ended in 2004 and was followed by the ENSEMBLES project under EU funding, and by a project to produce regional climate-change scenarios, CORDEX, under World Climate Research Programme sponsorship.

There have been a number of other studies on extreme weather and climate events in Europe. A large group led by Moberg analysed daily temperature and precipitation records for the period 1901–2000 and for stations in Europe west of 60° E (Moberg *et al.*, 2006) and constructed frequency distributions of the data. They found that the warming of daily maximum temperature during winter was stronger in the warm tail of the distributions than in the cold tail, although there were large regional differences in the temperature trends. The average winter precipitation totals over 121 European stations north of 40° N have increased significantly, by 12 % per 100 years, and similar trends were reported for the 90th, 95th and 98th percentiles of daily winter precipitation. For the summer season, they found weak if any trends in the precipitation totals, but noted that the summer precipitation may have become slightly more intense but less common.

Beniston *et al.* (2007) examined the model results from PRUDENCE, in which nine different regional climate models had been used to downscale scenarios from two global climate models (GCMs). The analysis provided a fairly comprehensive picture of a range of phenomena, although the results only provided a small sample of possible outcomes in terms of internal variations (Deser *et al.*, 2012) and GCM biases. They examined data on heat waves, heavy precipitation, wind storms and storm surges. According to the PRUDENCE results, Central Europe can expect to see the same number of hot days by the end of the 21st century as currently in Southern Europe, assuming the SRES A2 emission storyline (steady economic growth in a world without global climate agreements). Furthermore, heavy winter precipitation is projected to increase in Northern Europe and decrease in the south, while increases in extreme wind speeds were estimated for the latitude band 45–55° N. The increase in wind speed is expected to lead to more severe storm surges along the North Sea coastline.

Local strategic decisions and solutions required for effective climate adaptation action require information from local and regional climate projections. However, there are concerns that current models are not yet able to provide sufficiently reliable information on these spatial scales (Oreskes *et al.*, 2010; Palmer, 2011; Pielke Sr. and Wilby, 2012). For example, a recent commentary in *Science* (Kerr, 2013) suggested that regional climate modelling is often insufficiently validated. However, this commentary was based on a paper by Racherla *et al.* (2012), in which it was stated that it is *'unclear as to whether or not* [the regional climate models' ability to provide a better description of the local climatology] *translates into a better reproduction of the observed*

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[1] http://www.cru.uea.ac.uk/projects/mice/html/extremes.html
[2] http://www.cru.uea.ac.uk/projects/stardex
[3] http://prudence.dmi.dk/main.html
[4] http://www.cru.uea.ac.uk/projects/mice/FINAL_VERSION_MICE_REPORT.pdf
[5] http://www.cru.uea.ac.uk/projects/stardex/reports/STARDEX_FINAL_REPORT.pdf

climate change therein'. They also note that 'there is not a strong relationship between skill in capturing climatological means and skill in capturing climate change'. The problem is tied to the question of the minimum scales at which the driving global climate model which provides the context for the downscaling of the local response is skilful in the predictions it makes (Benestad *et al.*, 2008). Indeed, Racherla *et al.* observe that *'the most important factor is the skill of the driving global model itself, suggesting that highest priority should be given to improving the long-range climate skill of* [the global climate models]'. If the input used for regional climate modelling is unrealistic, there is little value in the downscaling – poor input leads to poor output. Furthermore, pronounced natural (internal) climate variations may imply large departures from a gradual change due to incremental increase in the greenhouse gas concentrations (Deser *et al.*, 2012).

The ENSEMBLES project (Linden and Mitchell, 2009) also addressed extreme events, basing its conclusions on a larger ensemble of global and regional climate models (GCMs and RCMs) than PRUDENCE. The study of climate extremes in the Mediterranean region, however, used results from only three transient runs with ENSEMBLES RCM simulations. Seven extreme indices were calculated, and all the model's simulations indicated that high temperatures would become even higher in the future. The results for precipitation, however, were less clear-cut. For mid-latitude storms, the ENSEMBLES results gave little indication of significant changes in the number of storms in the northern hemisphere, nor any significant trends in the intensities of the storms. While the conclusions about storms based on PRUDENCE focused on a limited region, the ENSEMBLES findings spanned the whole hemisphere. The two may not necessarily be inconsistent, as a shift in the storm tracks may in principle entail higher storminess in some regions, less in others, and no net change globally. The ENSEMBLES results, however, suggested an increase in the precipitation with the storm tracks, which could be associated with changes in extreme precipitation. However, the dependency between the precipitation and winds was not clear-cut. In addition to the model simulations, ENSEMBLES also generated the E-OBS gridded data set containing temperature, precipitation and pressure for Europe at a 0.25-degree resolution. Although this data product contains some of the best descriptions there are for European temperature and precipitation, it is widely recognised that this gridded product is not based on a dense enough network of station observations to provide reliable descriptions of extreme events.

A recent *Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation* (SREX; Field *et al.*, 2012), published by the Intergovernmental Panel on Climate Change (IPCC), provides a global overview of our current knowledge about extreme weather and climate events and their implications for society. The SREX report provides a general description for the entire world, but it gives a less detailed picture of change in Europe.

The study of extreme events is a relatively young field. Nevertheless, research on extreme weather and climate events is making rapid progress and new knowledge has been accumulated since the studies described in Field *et al.* (2012).

The purpose of the recently established projects VALUE (COST ES1102), SPECS (FP7), and ECOMS (FP7) has been to strengthen European networks for modelling extreme-climate and weather events and to provide a contribution to European climate services. The VALUE project has focused on evaluating downscaling methods and the description of extremes, while SPECS and ECOMS have focused on seasonal-to-decadal (s2d) predictions and the provision of the results from the projects. The focus on extreme events in SPECS will involve the downscaling of precipitation statistics based on recently identified patterns for the 24-hour precipitation distribution (Benestad *et al.*, 2012a). More recently started EU-funded projects (FP7) include the projects quantifying projected impacts under 2° C warming (IMPACT-2C[6]), and Enabling CLimate Information Services for Europe (ECLISE[7]), which have a stronger emphasis on the climate services aspect of the results.

This report assimilates the lessons learned in these European studies. It combines information from them with a review of the broader scientific literature and information about regional variations across Europe, impacts and adaptation strategies in an assessment of the current state of knowledge about past trends and likely future patterns of extreme weather.

1.3 Factsheets: summaries of evidence for European policy communities

Inevitably, this report is large, and the necessary assessment of evidence is demanding on the reader. As

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6. http://www.hzg.de/mw/impact2c/
7. http://www.eclise-project.eu/

part of the EASAC extreme weather project, this material has been recast in the form of factsheets, succinct and accessible summaries of the evidence and main findings associated with the key sections of the report.

The aim of the factsheets is to provide European decision makers and other interested groups and individuals with a summary assessment of the current state of knowledge about future patterns of extreme weather, recent trends and impacts. Planned factsheets also aim to provide some information about possible adaptation measures.

The factsheets contain key information about the main extreme weather phenomena, how such information is prepared and how it can be understood. They are designed in a form that will enable them to be updated as new information becomes available and the set could be expanded to include further topics as they emerge.

Currently available from www.dnva.no, the factsheets cover the understanding and use of statistics in extreme weather analysis, wind storms, precipitation and floods, temperature extremes and droughts and dry spells.

CHAPTER 2 STATISTICS OF EXTREMES, MODELS AND RISK MANAGEMENT

2.1 Definition of extremes

Extreme events are by definition rare, with magnitudes in the upper or lower part of the scale of variability. In a complex system such as the Earth's climate, extreme events recur in an irregular fashion, and the timing is unpredictable. The timing of the occurrences is therefore unknown, and extreme events may for all intents and purposes be regarded as stochastic (non-deterministic and sporadic). The discipline of statistical modelling, which assumes a degree of randomness, is therefore suited for describing extreme events. Moreover, the greatest challenges in understanding extreme phenomena often involve their intrinsic irregular nature and the small samples of extreme values available. Both these aspects are important to keep in mind in analysing extreme events. Zwiers *et al*. (2012) provided a descriptive perspective of extremes: *'a characteristic of extremes is that they are understood within a context – and thus seasonal or annual means may be "extreme" just as an unusual short-term event, such as a daily precipitation accumulation, may be extreme'*.

2.2 Underlying data – pre-processing

All knowledge of local climates and extremes is tied to measurements made over long time periods, statistical theory and physics-based atmospheric models. The statistics- and physics-based models involve two fundamentally different philosophies: the former extracts information from the empirical data while the latter derives relevant information by applying the laws of physics. The physics-based or process models, however, do include some empirical information, for example for calibrating parameters to describe sub-grid processes. Furthermore, they require real observations for proper evaluation and calibration. Real measurements are important for climate model development, for tuning models and for describing the statistical characteristics of small-scale processes which the models do not explicitly resolve – known as parameterisation.

Extreme value analysis requires long series of measurements for the identification of typical patterns in intensity and recurrence because, by nature, they are irregular and rare. Furthermore, it is extremely important that systematic errors and influences from non-climatic conditions are absent in these measurements, as interference from sources unrelated to the subject of interest affect the results.

Some extreme phenomena are also local in nature, which means that they are seldom seen in the measurements. Furthermore, such small-scale processes cannot be described properly in climate model simulations, as climate models describe mean conditions over a volume rather than exact values at any given location in space. Moreover, model simulations must be evaluated against the ground truth to quantify bias and uncertainties.

A great deal of work has been devoted to ensure that the data used in climatological studies reflect real climatic conditions, rather than changes in the instruments, observing practices or local environmental conditions such as urbanisation or the removal of trees. Measurements of extreme conditions can sometimes be difficult, as these often involve severely intense phenomena where the value of interest exceeds the calibrated range of the instrument, or that the instrument is blown or washed away by floods. In such situations, the measurements may underestimate the severity of extremes. The process of making sure that the climate data reflect real climatic conditions is known as homogenisation. Box 2.1 gives an example of homogenisation and the results it can give.

Statistical theory

Statistical models, on the other hand, involve well-defined mathematical constructs fitted to a set of data. A typical approach is to derive mathematical equations that describe a variable's frequency distribution, or its probability density function (pdf). The mathematical equations used to estimate the data distributions may involve different types, or families, of curves, such as the binomial, Poisson, Gaussian, exponential, gamma, Weibull, Gumbel, or Fréchet types. These describe a range of different shapes that characterise different statistical distributions.

The binomial distribution describes the probability of seeing a given number of events if there is a certain probability that these take place. This distribution is inherently associated with discrete events and probabilities such as coin flipping. In a similar vein, the

BOX 2.1 DATA HOMOGENISATION

One of the problems associated with the analysis of historic climate data is that data sets may be influenced by non-climatic factors, such as the relocation of monitoring stations, changes in the instruments, procedures used or alterations to the immediate physical environment of stations due, for example, to site redevelopment. To correct for these factors, a process known as homogenisation has been developed. By definition a homogenised data set is one in which the variations seen are caused only by variations in climate. In practice, homogenisation starts with basic quality control procedures and the creation of a reference time series of high-quality data. It is usually then possible to identify break points where something has happened to produce a step change in the data that can then be adjusted to account for change. Kuglitsch *et al.* (2010) produced a high-quality homogenised data set of daily maximum and minimum summer air temperatures from about 250 stations in the Eastern Mediterranean and used it to study the number, length and intensity of heat waves between 1960 and 2006. Statistical homogeneity tests had shown that many of these measurements, in the 1960s, were biased under heat wave conditions. Once these biases were corrected, regionally averaged heat wave trends were found to be 8 % higher than estimated in the past, suggesting that the heat wave increase in this region was higher than had been previously reported.

Poisson distribution describes the probability of a given number of events occurring in a fixed interval.

For example, the number of storms in a season is expected to follow a Poisson form if these events take place at random intervals. The number of events exceeding the 95th percentile over a period of time can then be described by a binomial distribution if the data are drawn from a random process. Hence, the Poisson and binomial distributions can be used to provide a reference against which the actual data are compared.

The Gaussian distribution, also known as normal distribution, on the other hand, is usually used to describe variables such as temperature. It provides more reliable information about the central values rather than the extremes in the tail of the distribution, as the probability associated with the Gaussian distribution become zero too quickly for values that differ from the mean by more than two standard deviations. The observations suggest that such extreme values are more common in weather modelling than the Gaussian distribution predicts. The exponential or gamma distribution is used, for example, to describe the frequency associated with 24-hour precipitation amounts and the Weibull distribution is often used to describe wind-speed statistics. The Weibull, Gumbel or Fréchet distribution are three different types of the general extreme value theory, and are used for describing extreme values in the tail of their respective distributions, being therefore specially relevant for extreme weather modelling.

Trenberth (2012) asked whether we can attribute extremes to climate change, and states *'the 4 % increase in water vapour becomes amplified in weather systems because it adds buoyancy to the air flowing into all storms, promoting them to become more intense and multiplying the effect'*. He also associated heavy and extreme rains with high sea surface temperatures, and argued that while global warming does not contribute directly to tornadoes themselves, it does influence the vigour of the thunderstorms which host them – through increased temperatures and moisture content. One central message from Trenberth is that while no events are caused by climate change or global warming, they do contribute to all events. In other words all weather events are affected by climate change because the environment in which they occur is warmer and moister than it used to be.

The take-home message conveyed by Trenberth (2012) can be captured through statistical theory. Probability density functions provide a description of a climate in terms of what values one can expect to see and how often they are expected to recur. A stable climate is a situation in which the pdf is the same all the time, whereas a climate change is by definition a pdf that changes shape or location. A changing pdf will, in general, imply changes in the tails of the distribution as well, and hence a change in the frequencies and intensities for extreme amounts. Moreover, a non-stationary pdf meteorological variable is equivalent to climate change, and a changing pdf with fixed tails is a limited, special and less likely example of a more general case, with changes over the whole range described by the pdf. Furthermore, for distribution types such as the exponential, the values in the extreme tails are determined by a small set of parameters describing the shape of the mathematical curve providing the pdf.

Climate models

Usually the term climate model refers to physics-based models, whereas extreme value models imply statistics-based models. The results from physics-based models are often in the form of a regular mesh grid or field holding different values, while the statistics-based models often provide results for a single location or a set of locations. Sometimes, the results from statistics-based models are gridded, but the process of gridding affects the representation of extremes if their spatial distribution is not smooth, and hence may introduce unwanted artefacts.

Essentially, global climate models are complex computer programmes that simulate the evolution of the atmosphere and oceans to obtain projections of temperature and other meteorological variables under different assumptions concerning the composition of the atmosphere and other influences such as variations in solar energy, so called external forcings. Almost all major climate models predict increases in global and regional mean temperatures throughout this century (see Deser *et al.*, 2012 for exceptions), under different scenarios concerning future population growth and techno-economic development. The consistency of these results has strengthened confidence in the understanding of global warming. However, there are also considerable variations among climate models. Computations through differential equations describe the evolution of all aspects of the atmosphere and oceans, mathematically described as high-dimensional state vectors, representing climate variables, by applying our understanding of climate dynamics and quantifying – integrating in terms of mathematics – processes over land, water, air and ice. With advances in science, technology and computing power, more processes can be represented explicitly at increasingly finer scales within climate models, but there still remains the need for approximations, for those processes that act at scales not explicitly represented. It is in these approximations that the source of large uncertainties resides.

The direct outputs from the climate models are variables solved by the equations describing the laws of physics, and include temperature, wind, pressure, humidity and precipitation. The values of these variables can provide diagnostics, for example for floods and droughts, by placing these outputs in the context of threshold values, probabilities, duration, and spatial extent and through interpretive models and analyses.

2.3 Statistics as used in the characterisation of extreme weather: how to read and understand them

Extreme-value statistics describe the probabilities associated with a quantity exceeding a given threshold value. There are well-defined mathematical expressions representing different pdfs which are used for quantifying expected return values. Probability density functions describe both climate change and natural variations associated with regional and local spatial scales. Deser *et al.* (2012) identified, in a set of controlled numerical model experiments, that even in pure model simulations there may be a strong presence of naturally occurring fluctuations due to large-scale atmospheric flows which may mask global warming even on continental scales. Their result may suggest that the range of variability could increase over time, so that the lower range suggests a near-stationary temperature while the upper range suggests a rapid warming. Nevertheless, the most likely description of the future is a general warming, and there is only a small probability of a near constant temperature for a particular location over a 50-year period.

The recurrence of record-breaking events can be used to make inferences about trends in extremes, where a test for independent and identical distribution (IID) can be made against the null-hypothesis that the pdf describing the process is stationary (Rios Insua *et al.*, 2012). The expected rate of new record-breaking events is well defined in terms of mathematical probability as long as there are no ties for the highest number and there is no upper bound (Benestad, 2008). Such an IID test can be used to assess the assumptions behind return-level analyses and extreme-value modelling: a stationary process where the pdf does not change, corresponding to a stable climate. However, the number of record events will also provide an indicator of trends in extremes and associated statistical significance. Another question is whether extreme events cluster in time or space, violating the condition of IID either in terms of long-term memory or that the character of the events is influenced by external conditions. In both cases, the probability of occurrence is conditional, and can be described through Bayesian methods. Clustering may be a consequence of regime shifts, for instance when the climate can reside in multiple stable states, such as glacial and interglacial periods or shifts from wet conditions in the Sahara to aridness. A violation of IID may imply that return-value analyses and risk analyses based on pdfs give invalid estimates for future probabilities and require means for predicting changes in the pdf or the percentiles (Benestad, 2007; Benestad *et al.*, 2012a).

2.4 Statistics and risk analysis in the characterisation of extreme weather

Climate change will have many consequences. Importantly, typical weather patterns will change, in particular the location and recurrence of extreme weather. Some extreme weather phenomena seem already to have changed and have had considerable impacts in Europe in terms of lives, economic losses and on the changes in lifestyle they have imposed, as later chapters illustrate. These changes will require policy responses both at European and local levels, and a framework for policy making is under development for extreme weather adaptation. The emerging framework is essentially risk analytic, relying on information about extreme weather phenomena and related risks.

Introduction

The robust warming signal predicted by global climate models is already acknowledged in global risk reports such as those of the World Economic Forum (World Economic Forum, 2013) and the International Risk Governance Council (IRGC; Renn, 2006). To provide policy-oriented information on the phenomenon of extreme weather change at a European level, as it is not possible to predict exactly what the future will bring in terms of extreme weather, a probabilistic approach is required with statistical models of extremes, in which the different phenomena are described in terms of their pdfs, which give the probability of an extreme event occurring. As such a wide range of possible outcomes will include those that have negative consequences, methods to understand the risks involved, which are provided by risk analysis, are needed.

A risk analytic framework for extreme weather change adaptation

The framework used in this report for adaptation to extreme weather is risk analysis. Risk analysis (Bedford and Cooke, 2001; Rios Insua *et al.*, 2009) is a systematic, analytical process for assessing, managing and communicating risks. Risk is usually defined as the product of the probability of an event and the severity of its impact, and the description of probability is therefore a central part of risk management. Using risk analysis, it is possible to understand the nature of unwanted, negative consequences to human life, health, property or the environment, as a first step in reducing and/or eliminating them – there is the ISO 31000:2009 standard for risk management. Typically, risk management involves four interrelated activities:

- Risk assessment. Information is collected on the extent and characteristics of risks attributed to a hazard, an extreme weather event in this case.
- Concern assessment. Used to understand the level of risk perception in a community, with a framing stage to clarify knowledge of the problem and an evaluation stage to assign trade-offs between risks and benefits.
- Risk management. A range of measures implemented to control the hazard, reducing its likelihood, mitigating and adapting to possible consequences, and to possible future events.
- Risk communication. Improving understanding of risk through an exchange of information and opinion about risk and risk-related factors amongst risk assessors, risk managers, communities and other interested parties.

This follows the Kaplan and Garrick (1981) characterisation of risks in terms of outcome scenarios, their consequences and the likelihood that they will come about, paving the way for risk-management processes. These entail a process for identifying and evaluating the risks to which a system is exposed as a prerequisite to the development of management systems. As a result of a systematic process of identifying and evaluating the risks to which a system is exposed, management strategies can be designed so that losses could be reduced or minimised, and costs of damage reduced as far as possible.

Brown and Wilby (2012) suggest that risk analysis should involve a bottom-up-approach, with the use of sensitivity testing, stress testing, and vulnerability analyses to identify key factors. Climate-change scenarios may then be used to provide plausible inputs for such analyses.

Modelling the degree of precision in extreme weather change

At the outset, relevant risks have to be identified, in this case risks associated with extreme weather phenomena and their consequences in Chapters 3 and 4:

- extreme temperatures;
- intense precipitation and floods;
- wind storms;
- convection-related events; thunderstorms and hail; droughts.

The relative importance of these threats can vary from region to region. This section outlines general statistical modelling approaches for describing the range and probabilities of plausible outcomes from extreme events.

Climate scientists recognise the need to take the range of uncertainties into account in presenting projections of future climate. As an example, the IPCC (2007; Solomon *et al.*, 2007) report had to integrate many individual pieces of research into an overall assessment and to characterise the variation amongst them. For this purpose, they recommended assessing the likelihood of a future event using broad categories, from very high confidence – at least a one out of ten chance, to very low confidence – less than a one in ten chance (see Glossary).

Given the substantial differences in model projections mentioned above, there are questions about how the ensemble of climate models can best be combined into a probability distribution of future climate change. The process of deciding which model to trust above all others is beyond the scope of this report, however, one possible strategy is to use all models that are available, synthesising the projections and their plausible ranges of outcome through a rigorous statistical analysis based on model averaging (Hoeting *et al.*, 1999; Tebaldi and Smith, 2010; IPCC, 2010). Furthermore, Deser *et al.* (2012) demonstrated that even one single model could produce a wide range of different future projections on 50-year time scales because of differences in descriptions of large-scale atmospheric flows. This strategy provides estimates of change and quantifies uncertainty in terms of probabilities and confidence intervals, depending on the available information. In combination with warnings about the limitations of modelling, such information is important for policy makers and stakeholders, as it gives a context for interpreting modelled outcomes. For instance, it is possible that all models have common shortcomings, which makes their interpretation difficult (Collins, 2007; Frame *et al.*, 2007). Indeed, there is growing acceptance of the need for statistical approaches to the assessment of uncertainty in climate change.

At a more local level, the class of models of most relevance to the field of extreme weather is that stemming from extreme value theory (EVT; Coles, 2001). This theory develops techniques and models for describing the unusual. Inherently, extreme values are scarce, meaning that estimates are often required for levels of a process that are much greater or smaller than have already been observed, implying an extrapolation with a smooth function from observed levels to unobserved ones, bypassing random statistical fluctuations. Extreme value theory provides classes of models to enable such extrapolation, which typically are based on observations of maxima, maximum rainfall, for example, minima such as minimum temperature, or exceedances over a certain threshold – rainfall beyond a certain threshold, for example. These correspond to the generalised extreme value distributions, which cover the Gumbel, the Fréchet and the Weibull models, and the generalized Pareto distribution. Such EVT models have been extended to multi-variate cases and to account for spatial issues. In extreme weather research, typical questions that we aim to address refer to whether, for example, extreme rainfall events are becoming more frequent – and whether this is related to global warming – which point towards the non-stationarity of the data and processes involved in extreme weather modelling, as described above. Extreme value theory models may be extended to cope with such issues by appropriately allowing some of the involved parameters to depend on time (Coles, 2001).

Once the relevant distributions are established, there are several ways of summarising them. The three we mention here, which are illustrated in later sections, are interrelated:

- To start with, we could summarise a distribution (pdf) through a number of percentiles. In the case of extreme weather events, it could be fixed at a high probability (p) percentile, say 0.99, which

would be the value above which there is a probability (1-p) of an event more extreme than the percentile value, say a temperature higher than this. For lower worse attributes, cold temperatures, drought, etc., the above p should be a low one.
- Return periods are also useful summaries of a particular distribution. They are estimates of the interval of time between extreme events, such as floods or temperatures, above a certain threshold. These can be used, for example, when designing infrastructure so that it is capable of withstanding an event of a certain return period, the 100 year storm and its associated intensity, for instance, over its lifespan. The return period is the inverse of the probability that the event will be exceeded in any one year. For example, a 25-year flood has a 4 % chance of being exceeded in one year. Special care must be taken if non-stationarities, typical in some climate change data, are detected. Non-stationarity means that the key properties of the pdf, the mean value of the variable, for example, vary over time or at different locations.
- Finally, probability of exceedance curves depict the probability that a certain value of a quantity of interest will be exceeded at a given location, over the period of interest.

2.5 Vulnerability analysis in extreme weather change

Vulnerability analysis deals with the potential impact of threats, should they materialise. This can be done from a global or local view, for example by assessing the vulnerability of a city, a river basin or a specific piece of infrastructure. Chapter 4 illustrates an approach at the European level, focusing on financial – insured and uninsured – losses.

Here, the local case, say of a city we aim to protect, is described. For a given event, say a flood of a certain magnitude, the damage it is likely to cause to the city infrastructure has first to be calculated. This damage will depend on many factors, but certain features of infrastructure would serve as good indicators of its potential vulnerability and, in particular, of its damage ratio – the ratio between the cost of repair and the cost of rebuilding. Again, it is necessary to assess the confidence limits of such a damage ratio, and to model the corresponding probability distribution. The damage ratio distribution for a specific event is then multiplied by the building replacement value to obtain the loss distribution for the corresponding building. These distributions are combined to get the appropriate aggregation level – at enterprise, neighbourhood, or city level.

Again, there are several ways of summarising such loss distributions, including:

Exceedance probability (EP) curves. In this case, the EP curve will describe the probability that various loss levels will be exceeded.

Return periods. As before, we could invert exceedance probabilities to obtain the corresponding return periods. For example, we can estimate the loss from a certain flood, find where that lies on the exceedance probability curve and invert the exceedance probability to deduce, for example, that if a flood has an exceedance probability of 4 %, its return period is 1 in 25 years.

Percentiles. Another way to assess the potential losses is through plotting percentiles around the EP curve.

Value at risk (VaR) and related measures. Percentiles are renamed in the finance literature through VaR as the threshold value, such that the probability that the losses over an investment over a given time horizon exceeds this value is the given probability level. For example, if a city has a 10-year extreme weather-related 5 % VaR of € 20 million, there is a 0.05 probability that the city will have losses beyond € 20 million over a decade with the current infrastructure. Informally, a loss of € 20 million or more in this city is expected in one year in 20.

Risk maps. For policy-oriented purposes, risk graphs relate probabilities of extreme events with expected losses (or distributions of losses). These may be powerful tools to communicate risks and their mitigation.

2.6 Concern analysis in extreme weather change

For policy purposes, a detailed knowledge of stakeholders' concerns, emotions, hopes and fears about the risk, as well as its likely social consequences, economic implications and political responses (World Bank, 2012), is as important as understanding the physical attributes of the risk. The second component of risk analysis provides a context for the results of a risk assessment through insights from risk-perception studies and interdisciplinary analyses of the social and economic implications of the risk.

Most studies tend to centre around financial losses and insured losses. However, extreme weather-related natural catastrophes may also have great humanitarian impacts entailing loss of lives.

Other concerns that might need to be considered include:

- damage and destruction of infrastructure;
- irreversible changes in environment;
- effects on biodiversity;
- inefficient use of land resources;
- population migrations that are environmentally displaced;
- competition for scarce resources;
- decrease in water quality and spread of diseases.

For policy purposes, multiple impacts can be aggregated through a multi-attribute utility function (Clemen and Reilly, 2004), which includes attitudes to risk.

CHAPTER 3 EXTREME WEATHER PHENOMENA AND THEIR CONSEQUENCES: THE SCIENTIFIC BACKGROUND

The scientific background to the analysis of extreme weather is to a very large extent driven by observations. These give evidence for recent trends in our climate and suggest how it might change in future. An understanding of phenomena, processes, and how different aspects of the climate interact provides essential information for interpreting these observations. In this chapter, the current state of understanding about the principal extreme climatic phenomena is described and assessed. A reliable analysis of past trends, an understanding of the factors that affect the trends and the way in which these will change in future because of global warming are all required to develop science-based adaptation strategies. The immediate and underlying causes of changes in extreme temperatures are discussed in the following sections, including the way in which extremes are affected by global warming.

3.1 Extreme heat and cold

In summary:

- Observations show a trend to more warm days, hot days and heat waves and fewer cold days over most parts of Europe since the mid 20th century.
- Most places in Europe are very likely to experience more hot and fewer cold extremes as the global temperature increases.
- The magnitude of hot and cold extremes is expected to increase faster than mean temperatures over large parts of Europe.
- The probability of occurrence of heat waves, such as those in 2003 in Europe or 2010 in Russia, is expected to increase substantially. For example, what is now a 1 in 50-year event may become a 1 in 5-year event by the end of the 21st century.

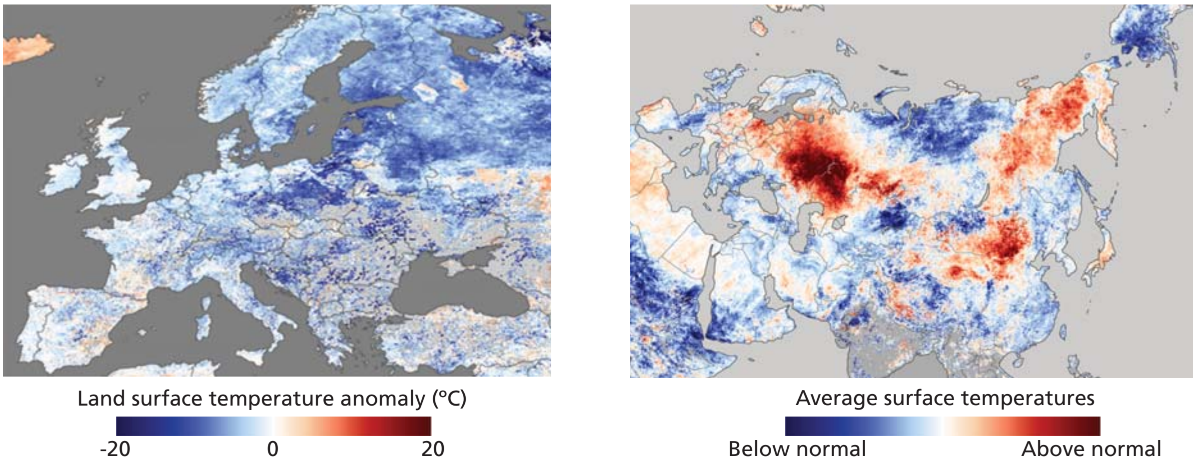
Introduction

Recent European summer heat waves and winter cold spells have had severe socio-economic and ecological impacts. The record-breaking 2003 and 2010 heat waves led to tens of thousands of heat-related deaths across Europe (Robine *et al.*, 2008; Barriopedro *et al.*, 2011), crop shortfalls, extensive forest fires and record high prices on the energy market amongst many other effects (Figure 3.1; Schär *et al.*, 2004; García-Herrera *et al.*, 2010). In the winters of 2005/2006 and 2009/2010, parts of Europe experienced unusually cold temperatures that caused travel disruption, cold-related mortality and high energy consumption (Cattiaux *et al.*, 2010).

Since adaptation to extremes of heat and cold is particularly difficult, changes in their frequency, duration or spatial extent and extremes of intensities never

Figure 3.1 The temperature difference in Europe between 11–18 December 2009 and the 2000–2008 average (left), and the average temperatures for 20–27 July 2010 compared to the normal for the period (right)

Source: (left) http://en.wikipedia.org/wiki/Winter_of_2009–10_in_Europe; (right) http://blogs.agu.org/wildwildscience/2010/08/11/amazing-nasa-images-of-russian-heat-and-smoke (image from NASA Terra satellite).



experienced before would make these phenomena among the most serious challenges to society in coping with a changing climate. In this section evidence for recent change in extremes of temperature is assessed and projections for the future are considered in the light of expected changes in the underlying mechanisms.

The loaded dice

First, however, it is important to understand how the observed average temperatures of the past decades might be expected to impact on extreme values. Temperature extremes occur in any stable undisturbed climate system, and result from natural variability. In a stable climate the number of new record-breaking events would be expected to decrease in time. However, this is clearly not the case for warm extremes, which have become more frequent, while cold extremes have decreased even more rapidly than theoretically anticipated (Rahmstorf and Coumou, 2011). Climate change affects the frequency and intensity of climate extremes through changes in the statistical properties of the temperature distribution (Figure 3.2). This is consistent with a global trend to significantly more warm nights and slightly more hot days, as identified in numerous temperature series across the globe (Frich *et al.*, 2002; Alexander *et al.*, 2006).

Allen and Lord (2004) make the point that any individual extreme event does not necessarily point to a trend and write *'it is not the case that "but for" past greenhouse-gas emissions these heat waves could not have occurred, nor that such heat waves will now happen every year'*. One way of looking at this is through an analogy with a known random system, the throw of a dice. What may sound complicated can then be understood with a loaded-dice analogy: if a dice is loaded to come up six and it comes up six, there is a clear sense in which the loading helped cause the result. If the loading doubles the chance of a six, it follows that half the sixes you get are caused by the loading. The question of which sixes is meaningless (Allen and Lord, 2004). In other words, an individual heat wave is by no means exclusively caused by human activity, however, in recent decades human activity has substantially increased the risk of heat wave in Europe and will very likely continue to do so given rising anthropogenic greenhouse-gas emissions.

Recent studies argue that human activity has indeed loaded the weather dice: that human influence on climate has increased the risk of an anticyclone causing a heat wave like that of 2003 by around a factor of four over what it would have been without recent climate warming (Stott *et al.*, 2004; Coumou and Rahmstorf, 2012; Francis and Vavrus, 2012).

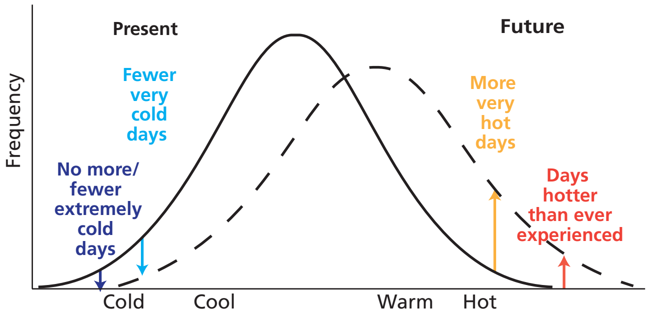
Hansen *et al.* (2012) consider how the climate dice has become more loaded recently, with a series of extreme summertime hot outliers that are more than three standard deviations (stdv) warmer than would be expected from the climatological record. These hot extremes typically covered less than 1 % of Earth's land surface area during the reference period (1951–1980), but now reach about 10 % of it. The results suggested that there were hot anomalies during 2006–2011, including in Europe, exceeding 3, 4 and 5 stdv of the 1951–1980 observations. Furthermore, Hansen *et al.* (2012) have argued that the extreme hot summers in France in 2003 and in Russia in 2010 almost certainly would not have occurred in the absence of global warming, and that for a future global warming of at least 1° C, anomalies exceeding +3 stdv would be the norm and +5 stdv should be commonly expected. Dole *et al.* (2011), on the other hand, concluded that the intense 2010 Russian heat wave was mainly due to natural internal fluctuations. Otto *et al.* (2012), however, drew the conclusion that the same event can be both mostly internally generated in terms of magnitude and mostly externally driven in terms of occurrence-probability, based on the results from a large ensemble simulation experiment with an atmospheric general circulation model.

Christidis and Stott (2012) show how recent extreme temperature events in the United Kingdom impact the

Figure 3.2 Potential changes in frequency and intensity of temperature and precipitation extremes in a changing climate

Current and potential future distributions are depicted by full and dashed lines, respectively.

Source: CH2011 (2011).



assessment of future risks. The winter of 2010/11, for example, was rare in the 352-year long central England temperature record, and anthropogenic greenhouse gas emissions have reduced the odds for such cold temperature anomalies occurring in future by about 50 %, with the estimated confidence range spanning 20 % and 80 %. Coumou and Rahmstorf (2012) show that the number of record-breaking monthly temperature extremes is now, on average, 12 times higher than expected, given a stationary pdf for temperature, mostly during summer.

Key driving processes

For better projections of future change, an insight into the underlying factors that drive temperature extremes is required.

The immediate causes of the 2003 and 2010 heat waves, for example, were persistent anticyclones. Such prolonged high-pressure systems produce subsidence, clear skies and, if centred over Central or Eastern Europe, warm-air advection from the Mediterranean and North Africa. The combinations of these processes produce typically prolonged hot conditions at the surface (Black *et al.*, 2004; Meehl and Tebaldi, 2004; Ogi *et al.*, 2005; Trigo *et al.*, 2005; Xoplaki *et al.*, 2006).

Recent work by Petoukhov *et al.* (2013) suggests that high-pressure systems may be influenced by large-scale waves in the atmosphere. They argue that the energy and propagation of these waves are restricted to certain latitude bands, and that a stronger polar warming will affect how the wave energy is concentrated within different latitudes. The waves are easily amplified by day-to-day weather, and the intensity of the high-pressure region is linked to the wave amplitude, whereas their duration is associated with the speed at which the wave moves.

Since the beginning of satellite measurements in 1979, the Arctic sea-ice extent has decreased faster than predicted by the state-of-the-art global climate models (Stroeve *et al.*, 2007). Recent work has suggested a connection between the Arctic sea-ice extent and extremes such as heat waves and extreme precipitation (Petoukhov and Semenov, 2010; Francis and Vavrus, 2012; Petoukhov *et al*., 2013) and there may be a number of plausible physical mechanisms connecting the Arctic sea-ice with weather patterns at lower latitudes. The north-south temperature gradient affects the wind structure through the thermal-wind equation, and may affect both the atmospheric jet stream and storm tracks. The warming over the Arctic may arise from a receding sea-ice cover exposing a warmer ocean surface in addition to a reduced albedo. Changes in high- and low-pressure systems in the Arctic may affect the blocking frequency and duration over parts of Europe (Petoukhov and Semenov, 2010). Different warming rates at different latitudes may also affect the propagation of planetary waves and result in stronger wave amplitude (Petoukhov *et al.*, 2013).

Most of the recent European summer heat waves have been preceded by a spring with low precipitation (Fischer *et al.*, 2007a; Vautard *et al.*, 2007). In 2003, the dry spring was associated with high insolation due to low cloudiness and an exceptionally early vegetation onset (Zaitchik *et al.*, 2006). Together these factors resulted in early and rapid soil drying that reduced evapotranspiration. The lack of moisture substantially amplified temperatures during these extremes (Ferranti and Viterbo, 2006; Fischer *et al.*, 2007b). The latter can also enhance the duration of a heat wave (Fischer *et al.*, 2007b; Lorenz *et al.*, 2010; Jaeger and Seneviratne, 2011) and even reinforce the pre-existing circulation anomaly (Fischer *et al.*, 2007a; Zampieri *et al.*, 2009).

Specific anomaly patterns of sea surface temperatures (SST) have been found to favour persistent anticyclonic patterns. In the case of the 2003 heat wave, the SST monthly means, averaged over the entire Mediterranean basin, from May to August were constantly above the long-term average (Grazzini and Viterbo, 2003). Although the persistent SST anomalies and the geopotential anomalies over Europe are likely to be closely linked, the exact role of high SSTs in the sub-monthly or seasonal heat wave is not clear (Beniston and Diaz, 2004). It is still under debate whether the SST anomalies over the North Atlantic and the Mediterranean contributed decisively to the 2003 heat wave (Black and Sutton, 2007; Feudale and Shukla, 2007) or if, on the contrary, they were induced by the intense positive tropospheric temperature anomaly (Ferranti and Viterbo, 2006; Jung *et al.*, 2006). While the role of Mediterranean SSTs for the 2003 heat wave is debated, it is well accepted that certain SST anomaly patterns influence circulation patterns that control heat waves. For instance Cassou *et al.* (2005) suggested that the SST anomalies in the tropical Atlantic Ocean significantly favour anticyclonic circulation regimes over Europe. Likewise, anomalous sea-ice conditions have been found to affect the likelihood of a heat wave occurring in Russia (Sedláček *et al.*, 2011). Also the timing of snowmelt (Barriopedro *et al.*, 2011) as well as changes in aerosols (Portmann *et al.*, 2009) and cloud cover are relevant mechanisms for understanding temperature extremes (Field *et al.*, 2012).

Interestingly, cold spells in winter are often associated with the same type of long-lasting high-pressure systems as summer heat waves. Depending on their location, these so-called atmospheric blockings, or anticyclones, can block the warm and moist winds from the North Atlantic and produce dry and cold conditions at their eastern edge (Trigo *et al.*, 2004; Cattiaux *et al.*, 2010).

Some studies suggest that retreating sea-ice in the Arctic may have an impact on weather extremes. Cohen *et al.* (2012) argued that reduced sea-ice extent has resulted in increased high-latitude moisture and more extensive snow cover in Eurasia. More extensive snow cover, they argue, induces more extreme large-scale cool conditions in winter through a dynamic response in the atmosphere. Based on a climate-model experiment, Petoukhov and Semenov (2010) suggested that reduced sea-ice concentrations in the Barents and Kara Seas might favour extreme wintertime cold events. Francis and Vavrus (2012) argue that sea-ice loss may result in slower eastward progression of Rossby waves (see Glossary) in the upper-level flow, which would cause associated weather patterns in mid-latitudes to be more persistent, and lead to an increased probability of extreme weather events that result from prolonged conditions, such as drought, flooding, cold spells, and heat waves. Benestad *et al.* (2010) and Orsolini *et al.* (2011) used a climate model to study the role of sea-ice in temperature and the circulation on seasonal scales. They found the response to be generally chaotic but the results suggested stronger systematic effects on the circulation patterns during autumn.

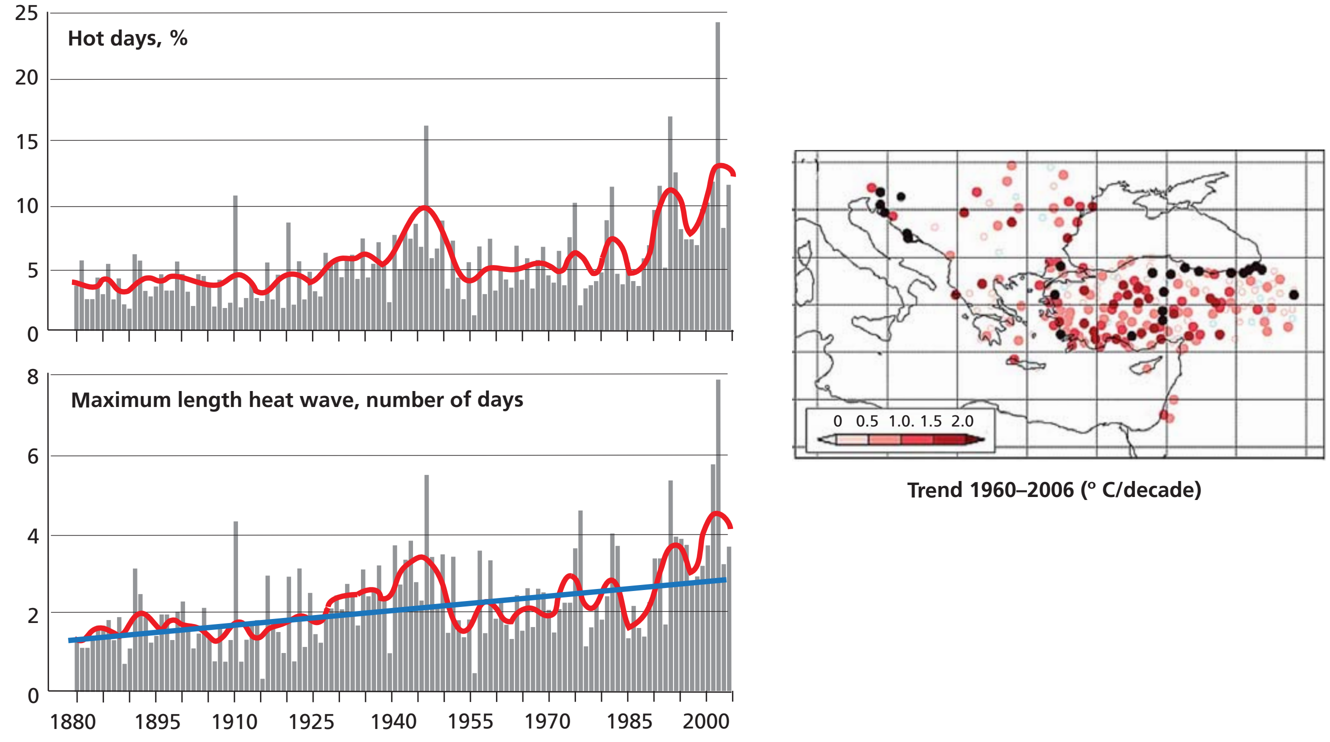
Observed changes in recent decades

Hot extremes

Over recent decades, the annual number of warm extremes has increased significantly in Europe as a result of an asymmetric pronounced warming of the upper tail of the temperature distribution (Klein Tank *et al.*, 2005; Moberg and Jones, 2005). Based on homogenised long-term temperature series at 54 European stations, Della-Marta *et al.* (2007) revealed that, on average, the length of heat waves has doubled and the frequency of hot days has almost tripled since 1880 (Figure 3.3).

Figure 3.3 Percentage of summer days when maximum temperature exceeds long-term daily 95th percentile (top left) and maximum heat wave duration in days, 1880–2005 over Western Europe (bottom left); and linear trends of heat-wave intensity 1960–2006, in ° C/decade (right)

Source: Della-Marta *et al.*, 2007.



Trend 1960–2006 (° C/decade)

BOX 3.1 HEAT WAVES

There are numerous observational studies documenting regional increases in the frequency of heat waves, for example in Portugal and the Eastern Mediterranean. A recent study shows that in Portugal there was a significant positive trend, particularly after 1976, in heat waves, tropical nights, summer days, warm spells and warm nights and days, while a negative trend was observed in cold extremes, particularly in winter (Ramos *et al.*, 2011). Pronounced increases in the number, intensity and length of heat waves have also been found for the Eastern Mediterranean basin, based on long, homogenised station time-series (Kuglitsch *et al.*, 2010; Efthymiadis *et al.*, 2011; see Section 3.1 for details of temperature increases in the Eastern Mediterranean).

The IPCC SREX report (Field *et al.,* 2012) concludes that there have been major increases in warm temperature extremes in Europe, with high confidence across the Mediterranean region. Over North and Central Europe, there is medium confidence in an increase in heat waves – their intensity and frequency. Furthermore, there has been a clustering of exceptionally warm European summers (Barriopedro *et al.*, 2011), and Cattiaux (2012) concludes that recent spring and autumn temperatures were also exceptionally warm – the 2011 spring in Western Europe was the second warmest, after 2007, for 1948–2011 while the 2011 autumn was the second warmest after 2006. Examples of trends of hot extremes for Southern Europe are given in Box 3.1.

Analysis by Diffenbaugh and Scherer (2011) indicates that the greatest likelihood of projected summer temperatures exceeding the warmest summers of 1980–1999 are in the dry subtropics. For the Mediterranean region, the mean percentage of June–August temperature exceeding the late 20th century maximum values after 2040 was estimated to be 60 %.

Cold extremes

In Northern Europe, cold extremes are usually associated with high-pressure systems, blocking events, and inversion situations arising from cloudless and calm conditions. Cold outbreaks are also caused by a flow of frigid Arctic air from the polar region. The cooling of air restricts its capacity to hold moisture, which may be deposited on the ground and vegetation in the form of frost and icing. A decrease in the water vapour concentration reduces the air's capacity to trap the outgoing heat radiation from the ground, letting the heat escape more readily to space. The occurrence of cold extremes depends on the frequency and duration of the winter-time blocking events and the atmospheric flow.

Cohen *et al.* (2012) in noting that recent trends in observed winter surface temperatures diverge from the simulated trends, argued that large-scale cooling has taken place over the last two decades across eastern North America and Northern Eurasia. Furthermore, they proposed that summer and autumn warming are associated with increases in high-latitude moisture and in Eurasian snow cover, which subsequently dynamically induces large-scale wintertime cooling. Francis and Vavrus (2012) also proposed that the sea ice may be linked to the atmospheric flow, and that the propagation of planetary waves have slowed due to a strong warming over the Arctic and a reduction in sea ice. They argued that this link could result in prolonging conditions, such as cold spells.

The occurrence of cold extremes depends on the way the temperature statistics change and on the question whether the variance increases with the mean value. Furthermore, most global climate models tend to overestimate the meridional pressure gradient, implying too mild and moist conditions in continental Europe and an underestimation of the frequency and duration of winter-time blocking events (van Ulden and van Oldenborgh, 2006, Brands *et al.*, 2013).

A World Meteorological Organisation (WMO) statement was issued in 2012 concerning the weather events observed that year (Press Release No. 966; for use of the information media – not an official record). One notable extreme event was a cold spell on the Eurasian continent from late January to mid-February 2012, with exceptional intensity, duration, and impact. The cold outbreaks in eastern Russia were associated with temperatures between -45° C and -50° C during the end of January 2012.

At many stations in Europe the number of frost days and cold nights and days has decreased significantly in recent decades (Klein Tank and Können, 2003; Alexander *et al.*, 2006;). An overall decrease in cold nights has been observed in Southwestern Europe and the Western Mediterranean; with greatest signals in Spain and southern France (Kiktev *et al.*, 2003; Klein Tank and Können, 2003; Alexander *et al.*, 2006; Brunet *et al.*, 2007; Rodríguez-Puebla *et al.*, 2010). Over the Eastern Mediterranean, the reduction in cold winter nights is less pronounced. Some areas in the Aegean and Black Seas and Turkey have even experienced a slight increase in cold nights (Efthymiadis *et al.*, 2011). In North and Central Europe many regions have experienced a trend to fewer cold days and nights since 1950.

There is a number of phenomena associated with cold conditions, which do not necessarily imply extreme temperatures. A number of these are discussed in Section 4.5, and involve rain on snow and freezing rain. Furthermore, the frequency of freezing and thawing – the number of zero-degree crossings – is influenced by the mean temperature, with higher numbers for areas with a mean winter temperature near 0° C. Recent analyses (Benestad, 2011) suggest a reduced likelihood of below-freezing mean winter, characterised by the temperature as measured at an altitude of 2 m T(2m), over Europe. The high mountain regions will still have below-freezing temperatures in 2100 given the SRES A1B scenario, and the greatest reduction in the probability for below-freezing mean winter temperature is expected in areas where the present winter conditions are around freezing – southern Sweden and Eastern Europe. The areas with current climatological temperature a few degrees below 0° C can expect to see more 0° C crossings in the future.

Projected temperature extremes

In summary, climate model experiments project:

- more frequent, longer and/or more intense heat waves or warm spells in all parts of Europe;
- more frequent warm days and nights – the greatest increase will be in Southern and Central Europe and smallest in Northern Europe;
- decreasing frequency of cold days and nights across all Europe.

The most likely cause of changes in temperature extremes is climate change. However, a recent model-based study by Deser *et al.* (2012) suggested that, at a regional level and over a 50-year time horizon, changes in extremes may be substantially higher or lower than the long-term warming caused by greenhouse gases because the large-scale atmospheric flow also changes irrespective of the long-term warming. Higher annual mean temperatures are expected to lead to more hot and fewer cold extremes. However, the magnitude of the changes and agreement among models varies with the definition used to describe the extreme and the characteristics of the event being considered – its time-scale, intensity, length and spatial extent, for example.

Heat waves in Europe are very likely to become more frequent and longer-lasting, mainly following an increase in seasonal mean temperatures (Barnett *et al.*, 2006; Fischer and Schär, 2009; 2010). As a result, the probability of occurrence of recent events such as the 2010 Russian heat wave would increase substantially – by a factor of 5–10 by the mid century (Barriopedro *et al.*, 2011; Dole *et al.*, 2011). Extremely hot summer temperatures, as seen in 2003, are projected to be exceeded every second to third summer by the end of the 21st century (Schär *et al.*, 2004; Fischer and Schär, 2010).

The temperature departures during the hottest days are expected to increase substantially more than the corresponding mean local temperatures in Central and Southern Europe as a result of enhanced temperature variability on inter-annual to intra-seasonal time scales (Schär *et al.*, 2004; Alexander *et al.*, 2006; Clark *et al.*, 2006; Fischer *et al.*, 2007a; Kjellström *et al.*, 2007; Vidale *et al.*, 2007; Fischer and Schär, 2009; 2010; Nikulin *et al.*, 2011). Climate models and observational studies suggest that this amplification occurs through soil moisture-temperature feedbacks (Seneviratne *et al.*, 2006; Fischer *et al.*, 2007a, 2007b; Lenderink *et al.*, 2007; Vidale *et al.*, 2007; Fischer and Schär, 2010; Hirschi *et al.*, 2011). Clark *et al.* (2010) demonstrate that even in scenarios where the global temperature change is limited to 2° C above pre-industrial levels, the intensity of temperature extremes in Europe may change by more than 6° C.

Surface temperatures, from a multi-model ensemble, downscaled and gridded based on geographical information, suggest the strongest increases in the mean June-August temperatures in regions that already are characterised by hot, dry summer conditions (Figure 3.4, Benestad, 2011). For the hot and dry low-lying Mediterranean regions, the projected change in the

BOX 3.2 IPCC SCENARIOS

Scenario descriptions based on those in the *IPCC Fourth Assessment Report* (Solomon *et al.*, 2007)

A1

The A1 scenarios are of a more integrated world. The A1 family of scenarios is characterised by:

- rapid economic growth;
- a global population that reaches 9 billion in 2050 and then gradually declines;
- the quick spread of new and efficient technologies;
- a convergent world – income and way of life converge between regions. Extensive social and cultural interactions worldwide.

There are subsets to the A1 family based on their technological emphasis:

- A1FI – an emphasis on fossil-fuels (Fossil Intensive);
- A1B – a balanced emphasis on all energy sources;
- A1T – emphasis on non-fossil energy sources.

A2

The A2 scenarios are of a more divided world. The A2 family of scenarios is characterised by:

- a world of independently operating, self-reliant nations;
- continuously increasing population;
- regionally oriented economic development.

B1

The B1 scenarios are of a world more integrated, and more ecologically friendly. The B1 scenarios are characterised by:

- rapid economic growth as in A1, but with rapid changes towards a service and information economy;
- population rising to 9 billion in 2050 and then declining as in A1;
- reductions in material intensity and the introduction of clean and resource-efficient technologies;
- an emphasis on global solutions to economic, social and environmental stability.

B2

The B2 scenarios are of a world more divided, but more ecologically friendly. The B2 scenarios are characterised by:

- continuously increasing population, but at a slower rate than in A2;
- emphasis on local rather than global solutions to economic, social and environmental stability;
- intermediate levels of economic development;
- less rapid and more fragmented technological change than in A1 and B1.

95th percentile of the ensemble results suggests 4–5° C increase by 2100 (SRES A1b, CMIP3 climate model ensemble; Box 3.2). Similarly, using a regional climate multi-model experiment, Fischer and Schär (2010) projected that under a scenario of a future world with very rapid growth and energy balanced across all sources (Box 3.2; Scenario A1B) the maximum heat wave intensity would increase by 4–6° C over Central and Southern Europe, which is substantially more than the projected change in mean summer temperatures. The greatest changes in heat-wave frequency are projected for Southern Europe (Fischer and Schär, 2009) where the frequency of hot summer days would increase from 5 % at the end of the 20th century (per definition) to about 65 % at the end of the 21st century – 40 % in Central Europe, under an A2 emissions scenario (Box 3.2). According to the IPCC SREX report (Field *et al.*, 2012), some projections of future global warming suggest that the most substantial increase in the high temperature percentiles may take place over Western Europe, specifically France, even if the largest mean warming is expected for the Mediterranean region. Furthermore, for Central and Eastern Europe, changes in extremes may be due to changes both in the mean and the variability. However, these results have to be treated with caution as much remains to be done to validate such detailed output from the models used.

A number of studies suggest that winter cold extremes are expected to become rarer (Tebaldi *et al.*, 2006; Nikulin *et al.*, 2011; Orlowsky and Seneviratne, 2012). Interestingly, cold extremes are also expected to warm more than the local mean temperatures as a result of reduced temperature variability related to declining snow cover (Gregory and Mitchell, 1995; Kjellström *et al.*, 2007; Fischer *et al.*, 2011). Nevertheless, recent studies

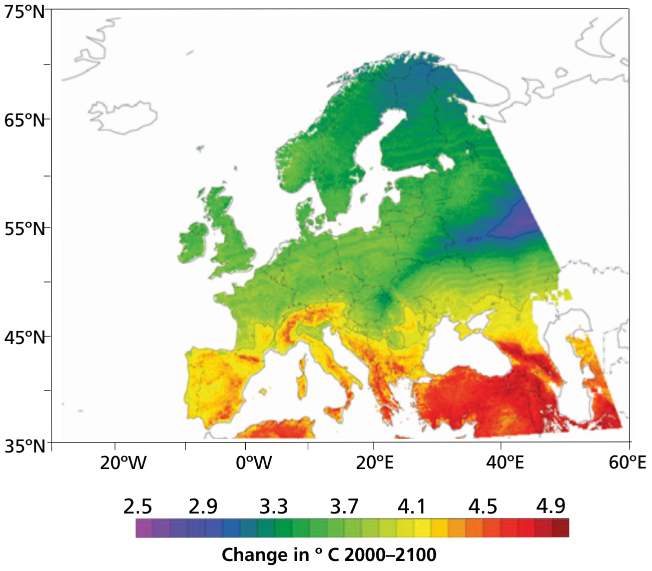


Figure 3.4 Increase in hot summers, taken as the 95th percentile for June–August mean temperature
The 95th percentile was derived from empirical-statistical downscaling of CMIP3-projected mean temperatures following the SRES A1b scenario, where the ensemble of models (~50 GCM simulations) describe both fluctuations associated with large-scale atmospheric flow and model differences. The downscaling was performed for 495 different stations, and the map was generated through a combination of regression to geographical covariates and residual kriging, a standard method used to fill in values at locations where there are no measurements.
Source: Benestad, 2011.

suggest that in Europe some intense cold winter spells may still occur in the second half of the 21st century (Sillmann and Croci-Maspoli, 2009; Kodra *et al.*, 2011; Figure 3.5). Cohen *et al.* (2012), on the other hand, suggest that a reduction in the Arctic sea-ice extent may lead to more cold spells, arguing that the sea-ice cover affects the Eurasian November snow-cover extent, which subsequently affects stratospheric conditions that later affect atmospheric circulation and atmospheric blocking. Petoukhov and Semenov (2010) also suggested that reduced Arctic sea-ice cover could lead to more cold spells. They used a GCM to study the atmospheric response to retreating sea-ice, and observed that the exposed sea had a tendency to give rise to high-pressure systems that are responsible for extreme cold winter conditions over Europe. Lockwood *et al.* (2010), on the other hand, analysed central England's temperature, and proposed that cold UK winters have historically coincided with low solar activity. They also pointed out that their findings were consistent with the solar influence on the occurrence of persistent blocking events in the Eastern Atlantic.

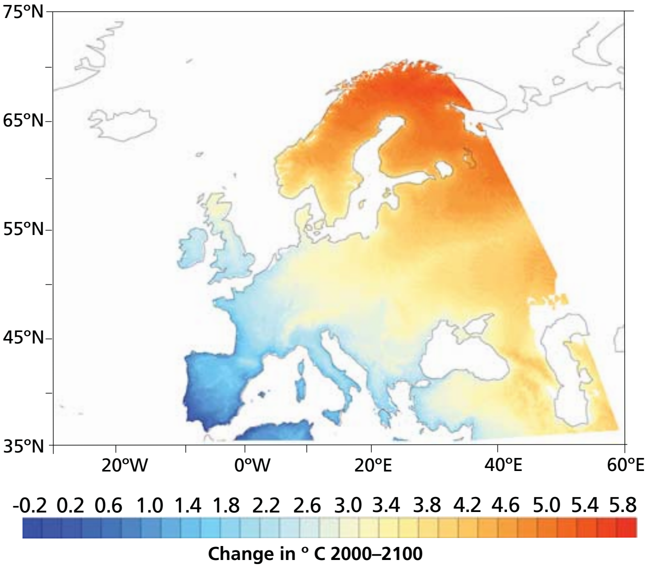


Figure 3.5 Changes in cold winters, represented by the 5th percentile for December–February mean temperature
Similar to Figure 3.4.

To conclude, heat waves and cold spells depend on several factors. The mean temperature is an important factor; it sets the base-line for temperature variations and it is increasing over time. It is the variations around this base-line that define extreme temperature events. These variations are associated with the large-scale circulation patterns known as blocking highs. The heat waves are expected to become more severe as the base-line slowly shifts to higher values, but conditions affecting the frequency of blocking highs may be sensitive to changes in the north-south temperature differences, sea surface temperatures, sea-ice cover, and soil moisture. According to Palmer (2011), climate models cannot predict future recurrences of blocking highs with great confidence because they still use a mesh that is too coarse and we do not know if they account for all relevant aspects.

Regional case studies

Although most temperature projections are made on the basis of model studies in which the geographic scale is large (Figure 3.9), observations are made at a local level, giving a finer scale in the analysis of past patterns of extreme temperature. From studies of long-term data sets it emerges

BOX 3.3 TEMPERATURE EXTREMES

Southwestern Europe (Portugal)

Climate model simulations for continental Portugal in 2071–2100 indicate a mean increase in maximum temperature ranging from 3.2° C for the B2 scenario to 4.7° C for the A2 scenario, relative to the end of the 20th century (Ramos *et al.*, 2011; SIAM II, 2006). For minimum temperatures the results were similar, with increases for summer (spring) ranging from 2.7° C (2.5° C) in the B2 scenario to 4.1° C (2.9° C) in the A2 scenario (Ramos *et al.*, 2011; SIAM II, 2006). High temperature extreme indices at the end of the century are expected to increase, while the cold extreme indices decrease.

Eastern Europe

From the gridded data set E-OBS (V7), based on observations from the ENSEMBLES project, it is possible to get some idea about trends in extreme temperatures for 1950 and 2011, keeping in mind that some studies, such as Kyselý and Plavcová (2010), suggest that E-OBS has particularly large biases in hot extremes over the Czech Republic, due mainly to a relatively sparse network of observational data. The E-OBS can nevertheless provide a reasonable description, albeit with inaccuracies, of large-scale phenomena such as maximum temperature associated with blocking highs. Over parts of Eastern Europe, a crude regression-based trend analysis of the 99th percentile of the annual daily maximum temperature suggested trends of 0.2–0.6° C/decade at latitudes above 55° N, but also some isolated regions with negative trends in the vicinity of the Carpathian mountains.

Eastern Mediterranean region

Temperature extremes in the Eastern Mediterranean have changed more than in the general record for Europe according to recent analysis. High-quality homogenised daily maximum and minimum summer air temperatures from about 250 stations in the area were used to study the number, length and the intensity of heat waves between 1960 and 2006 (Kuglitsch *et al.*, 2010). Statistical homogeneity tests have shown that many of the measurements in the 1960s were biased under heat wave conditions. Correcting for these biases, regionally averaged heat-wave trends were found to be 8 % higher than estimated in previous studies. Since the 1960s, the mean heat-wave intensity, length and number across the Eastern Mediterranean region have increased by a factor of 7.6 ± 1.3, 7.5 ± 1.3 and 6.2 ± 1.1 respectively, based on the daily 95th percentile during the July–September season of 122 days for 1969–1998.

In this analysis, for each June–September day, a 95th percentile was calculated from a sample of 15 days, seven days on either side of the respective day, using data for the 1969–1998 period. A heat wave was defined as a period of three or more consecutive days and nights not interrupted by more than one non-heat day or night. A hot day/night was defined as a day/night where the daily

that the pattern of extreme weather has varied across Europe in the past. It seems that the changes observed in Southwestern Europe (Box 3.3) are less severe than those seen in the Southeastern Mediterranean (Box 3.3). In the rest of Eastern Europe, regional studies (Box 3.3) suggest that past changes in extreme heat in latitudes above 55° N have been higher than the global mean of 1.3° C/decade given in the *IPCC Fourth Assessment Report*. Projections suggest that the Eastern Mediterranean will have a larger increase in extremes than the rest of Europe, with the expectation that the number of hot days will increase from today's level by 20–40 by the end of the century (Box 3.3). It is important to keep in mind, however, that climate models may overestimate regional amplification caused by global warming. Boberg and Christensen (2012) found that model simulations of intense summer warming around the Mediterranean may be partly caused by model deficiencies. All the models that they examined exhibited increased temperature biases with higher temperatures, based on the results of the ENSEMBLES project.

3.2 Extremes of precipitation

In summary:

- Intense precipitation in Europe exhibits complex variability and a lack of a robust spatial pattern.
- In general, studies point to a trend over recent decades towards more heavy precipitation.
- Seasonal changes have also been noted with an increase in the frequency and intensity of winter precipitation in Central and Eastern Europe.

temperature maximum/minimum ratio exceeded the 1969–1998 daily 95th percentile for July–September (Kuglitsch *et al.*, 2010). This analysis suggests that the heat-wave characteristics have increased in the region at a higher rate than was previously reported.

Single model simulations do not provide information about the range of different possible future local climate conditions associated with different large-scale atmospheric flow (Deser *et al.*, 2012). Individual climate models also misrepresent different aspects of local climatic phenomena to some degree. Hence, if one looks at ensembles of climate simulations, for example from the ENSEMBLES project, it is clear that projected patterns of regional change are far from robust. Nevertheless, single runs can provide a glimpse of a possible future climate, given a set of conditions and a realistic climate model. Keeping these caveats in mind, long-term meteorological datasets and the projections from the PRECIS regional climate model for the 21st century, based on the intermediate IPCC SRES scenario A1B (Lelieveld *et al.*, 2012), suggests a continual, gradual, and relatively strong warming of about 3.5–7° C between the 1961–1990 reference period and the period 2070–2099. The projected warming is approximately spatially uniform for night-time minimum temperatures, whereas the increase of maximum day-time temperatures is more rapid in the north, the Balkans and Turkey, for example, than in the south. Towards the end of the 21st century, this will reduce the meridional temperature contrast by about 2° C. Moreover, these figures provide only an illustration of a future climate, as they were derived with just one model. Other models may provide a slightly different picture.

By the end of the century the number of hot days per year, those with maximum day temperatures above 35° C, may, according to some projections, increase by up to 15 days over the higher elevation areas and 20–40 days for most of the domain. The strongest increase, of more than two months, is projected over the Levant and the North African coast, approaching the conditions experienced in the Gulf region during the reference period. The increase in number of tropical nights, those with minimum night-time temperatures above 25 °C, is equivalent to almost a month at the low-elevation areas of the Balkans, the Levant, the North African coast and southern Iran, and two months and more in the southeastern part of the region as well as some locations around the Aegean Sea and Cyprus. The notable exception is the small increase projected over mountainous areas of less than 10 days. It appears that the sub-regions for which the largest increases in the tropical nights are expected, may conversely experience the smallest increases in hot days; and the reverse also applies. Nevertheless, the overall heat stress could be very large. Since tropical nights tend to exacerbate the adverse effects of daytime heat stress, the increase in the number of tropical nights by more than 60 days is of great concern.

It is expected that:

- in general, across Europe there will more frequent events of high precipitation and fewer events of moderate or low precipitation in future;
- winters will, in general, be wetter and summers drier;
- there will be differences in change across Europe, with drier conditions in Southern Europe and wetter conditions in Northern Europe.

The hydrological cycle and extreme precipitation

The hydrological cycle is the cycling of the planet's freshwater. It encompasses water vapour, water droplets and ice in the air, precipitating hydrometeors, groundwater, lakes, rivers, snow and ice on the ground, as well as a small fraction of the oceans, and sea-ice. Of crucial importance for the hydrological cycle are the fluxes of water between the Earth's ground surface and the atmosphere – evaporation and precipitation. Atmospheric circulation and turbulent mixing may efficiently transport atmospheric moisture over large distances from its origins at the Earth's surface before it eventually is removed as precipitation. Atmospheric dynamics provide conditions for precipitation, but the release of latent heat during condensation also influences the dynamics as a positive feedback by reinforcing the motions that caused the condensation in the first place.

Long dry spells, potentially leading to droughts, and high precipitation intensities, which may cause flooding, are two aspects of extreme precipitation. Since the duration of dry spells and high precipitation intensity are two equivalent aspects of the strength of the hydrological cycle (Trenberth *et al.*, 2003; Trenberth, 2011), Giorgi *et al.* (2011) introduced a quantity that combines them into one dimensionless number (HY-INT). Their analysis demonstrated that this hydro-climatic intensity is a robust indicator of global warming. This includes changed risks for systems that are sensitive to either wet or dry extremes. While trends in precipitation intensity and dry-spell duration may be masked by strong inter-annual and geographical variations, the trend in the combined indicator (HY-INT) is considerably more significant.

A global hydro-climatic analysis, based on budget numbers for the recent state of climate, was given by Trenberth *et al.* (2003). Approximately 30 % of the global average of 25 mm precipitable water – water drops suspended in the air, ca. 7.5 mm – is in practice available for precipitation on average. According to Trenberth *et al.* (2003), about 45 mm/day is probably close to the global average rate of precipitation when and where it occurs, while the total global average flux of precipitation is about 2.8 mm/day. This indicates both that only 1/16 (~2.8/45 = 6 %) of the Earth's surface experiences precipitation at a given time, and that air over an area that, on the average, is 16 times as large as the precipitation area (a scale 3–5 in linear transport distance) is involved in the dynamics responsible for the precipitation release. However, 45 mm/day during precipitation is highly uncertain and probably dominated by the tropics. It is difficult to determine this value precisely, and an estimate based on the European Centre for Medium Range Weather Forecasts' state-of-the-art reanalysis data, often called ERA-interim or ERAINT, for 2011 yields a figure that is more like 8.4 mm/day, with regional maxima associated with the inter-tropical convergence zone and the South Pacific convergence zone over the oceans, as well as land-regions of Southern Asia, Indonesia, the southern USA and the equator. It is problematic, however, to use reanalysis data such as the ERAINT to discuss the hydrological cycle, since the data-assimilation procedure precludes a closed-cycle budget, and there is no global constraint imposed on the hydrological cycle when doing the data-assimilation. An analysis of the water mass budget over the oceans and land area suggests a mismatch of about 20 % (Trenberth *et al.*, 2011). The rain gauges from the global daily climate network (GDCN; over land only) data, on the other hand, provide the actual measured amounts, and the measurements suggest that the maximum mean precipitation intensity over land is 26 mm/day over India.

This analysis implies that atmospheric dynamics and the associated transport of moisture are crucial in the determination of the precipitation climatology. Trenberth (1998) estimated that ca. 70 % of the moisture in extra-tropical cyclones comes from redistribution of pre-existing airborne moisture, while 30 % comes from evaporation from the surface. For small-scale systems like convective showers, evaporation is probably too slow to contribute significantly during the development. Trenberth *et al.* (2003) also indicated that precipitation occurs up to 30 % of the time poleward of 60°, while only 5–10 % in the tropics.

In order to understand the nature of different aspects of extreme precipitation, it is useful to trace the recycled moisture inside a region from the part that contributes to the general moistening of the air and is transported through a region. Following Trenberth (1999), the intensity of the hydrological cycle, or the precipitation efficiency, is the fraction of moisture flowing through a given region that is removed as precipitation within it.

The nature of the potential impacts of extreme precipitation varies with the length of its accumulation period and the spatial scale of the event. Extreme precipitation intensity over periods of a fraction of an hour to a few hours and, in very rare cases, a day, requires a strong convergence of atmospheric water vapour into the system in combination with dynamical processes causing efficient condensation and precipitation over confined areas. Often the dynamics that cause vertical motion and condensation also contribute to convergence of moisture. This is indeed the case for the typical summer-time convective storms, but also in frontal precipitation enhanced by slantwise convection causing strong bands of high-intensity precipitation.

High precipitation amounts in winter often occur when relatively cold Arctic air passes over open lakes or sea-areas causing vigorous convective snow or rain storms in the advancing cold air. The precipitation can be further enhanced by orographic lifting – where geographic features cause air to rise, the airflow over mountains, for example – but tend to dissolve further inland.

A special kind of weather system, occasionally occurring when relatively cold Arctic air passes over open sea areas adjacent of the northernmost parts of Northern Europe, is the so-called polar lows. These can be particularly dangerous over the ocean and in coastal regions due to their swift development and small spatial scale. They may occur as far south as the British Isles, the Netherlands and Denmark, but are recurrent during winter further north. These phenomena are not resolved in climate models at present.

Extreme precipitation may also be associated with large amounts occurring over longer periods, such as weeks to seasons or possibly longer. In such cases, the short-term intensity need not be particularly extreme, but the duration may cause precipitation to exceed regional evaporation over time by amounts that may cause impacts on nature and society. One such example was the sustained precipitation over Northwest Europe in autumn 2000, including the southern British Isles and Southeast Scandinavia. This episode was associated with a strong positive Scandinavia pattern with a high-pressure anomaly over Northeast Scandinavia and a low-pressure anomaly over the British Isles (http://www.cpc.noaa.gov/data/teledoc/scand.shtml). Another 3-month episode in Bergen, Norway was observed in November 2004 through January 2005 (Figure 3.8).

The summer of 2007 over the British Isles is an example of both aspects of extreme precipitation. The period as a whole was extremely wet, and a line of convective storms passed over southern England on 20th July which produced month-scale precipitation amounts of up to an observed 147 mm over approximately 2 hours, causing extensive and severe flooding as well as traffic havoc (Mayes, 2008).

Droughts are extreme precipitation events associated with extensive dry spells over continental regions leading to exhausted moisture sources and hence considerably reduced or vanishing evaporation. In very extreme cases practically all solar radiation will contribute to increased ground surface temperatures regionally. A recent example of such a situation in Europe occurred in June, July and August 2003 (Schär *et al.*, 2004).

Sources for extreme precipitation in Europe

In Europe the 500 km scale recycling ratio was estimated by Trenberth (1999) to vary from less than 4 % in the north to more than 12 % in the south, indicating that precipitation in Northern Europe depends crucially on horizontal advection of moisture from remote regions. In Northern Europe the recycling ratio varies considerably between seasons with a minimum in winter, as the synoptic-scale atmospheric transport is large in winter and small in summer while continental evaporation is the reverse.

It should be noted that a large recycling ratio over continental regions makes them vulnerable to droughts in situations when the local sources of surface evaporation are exhausted. This is well known in the Mediterranean, and many climate projections predict dryer conditions in response to anthropogenic forcing. Projections also predict increased risk of droughts further north during summer, when under present conditions the recycling ratio is at its maximum.

This interpretation of recycling as a risk factor for droughts is somewhat simplistic, since changes in atmospheric flow patterns responsible for the remote transport may also influence regions with low recycling ratios. For example, in deserts and semi-arid regions, the very low ratios are not indicative of a large horizontal influx of moisture but rather of zero local evaporation. Also in Mediterranean areas, such as the Iberian peninsula, the local evaporation contributing moisture to convective storms in summer depends on a horizontal moisture influx during the rainy winter season associated with synoptic-scale cyclones. If a positive phase of the NAO, a high NAO index, prevails during winter, which was the case during the 1990s, this can precondition summer droughts.

Advanced methods for estimating evaporation and precipitation along actual atmospheric transport pathways have increased the understanding of recycling versus large-scale redistribution of moisture in connection with precipitation (Stohl and James, 2004; Stohl *et al.*, 2008; Gimeno *et al.*, 2011). The predominant transport over intercontinental distances takes place in elongated narrow filaments, so-called atmospheric rivers. These filaments are confluent atmospheric flow structures brought about by non-linear deformation fields known to generate extra-tropical fronts. They can also be regarded as part of the warm conveyor belts of extra-tropical cyclones. The transported moisture is predominantly precipitated out in connection with the synoptic cyclones when they reach maturity over the eastern parts of the extra-tropical ocean and adjacent land-areas, such as over Northern Europe.

Gimeno *et al.* (2011) present a map of a transport analysis that indicates a strong contribution of moisture originating over the North Atlantic sub-tropics to the winter-time precipitation in Northern Europe. It follows from this that the strength and position of the Northern Atlantic polar front and the associated tracks of synoptic-scale cyclones are crucial for the winter-time precipitation in Northern Europe (Bengtsson *et al.*, 2006). There is still a substantial degree of uncertainty about historic changes in the storm tracks and the question whether the storm activity has changed over time. A new initiative, known as inter-comparison of mid-latitude storm diagnostics (IMILAST), addresses this important issue of tracking and analysing storms, and comparison between storm-track analysis over shorter times has revealed differences in the description of the storm statistics, even when based on the same data (Neu *et al.*, 2012).

It has been difficult to say whether the decreased activity previously reported in the mid-latitude and increases in the high latitudes reflects external forcing or low-frequency internal variability. Over the period 1871–2010, the number of cyclones and their mean intensity have, according to Wang *et al.* (2012), increased over the high latitudes of the North Atlantic and decreased over the Arctic. Krueger *et al.* (2012), on the other hand, argued that the reanalysis of 20th century data made by Compo *et al.* (2011), known as 20CR, on which Wang *et al.* (2012) based their analysis, was unsuitable for the identification of trends in storminess in the early part of the record, especially over the Northeast Atlantic. The basis on which they made their claim was the differences in variability and long-term trends in independent data, and Wang *et al.*'s conclusion may be sensitive to substantial inhomogeneities in the 20CR.

In summer, the situation does not depend on transported moisture to the same extent, but rather on the occurrence and strength of convective storms.

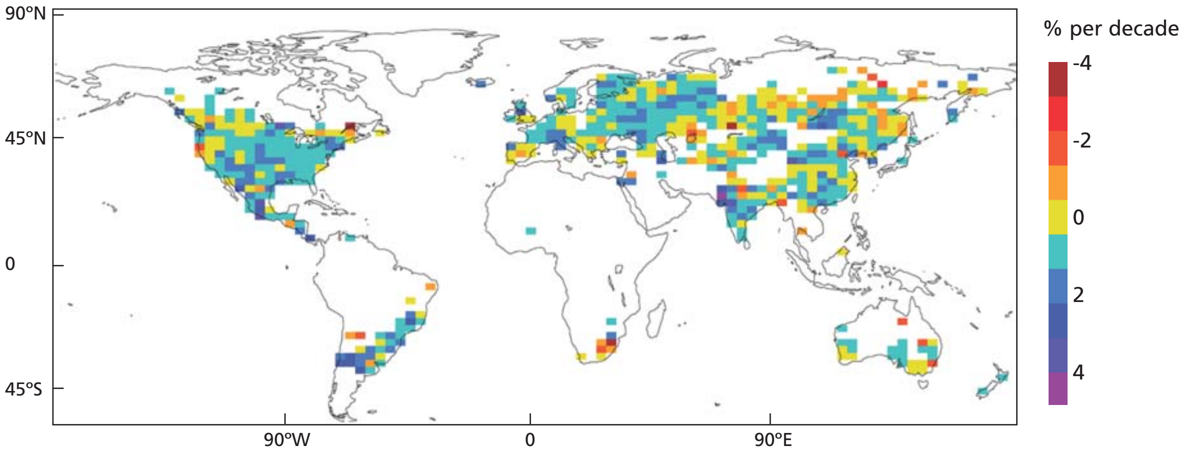
Historic trends in intense precipitation

Although there is an increasing body of evidence of the ongoing warming of the atmosphere, precipitation changes have been less regular. There have been increases over land north of 30° N over the period 1901–2005, and decreases over land between 10° S and 30° N after the 1970s have been noted by Trenberth *et al.* (2007) on the basis of historic observations. Over the past 50 years, heavy precipitation events have been on the rise for most extra-tropical regions (Groisman *et al.*, 2005; Trenberth *et al.*, 2007). This includes widespread increases in the contribution to total annual precipitation from very wet days, days in which precipitation amounts exceed the 95th percentile value, in many land regions (Figure 3.6). This corresponds to the observed significant increase in the amount of water vapour in the warmer atmosphere and is consistent with a standard equation used in chemistry known as the Clausius-Clapeyron law (see Glossary). However, the rainfall statistics are strongly influenced by inter-annual and inter-decadal variability. There are problems with data availability, in general, and also with data homogeneity and accuracy.

Figure 3.6 Observed trends, in % per decade for 1951–2003, in the contribution to total annual precipitation from very wet days (95th percentile)

Trends were only calculated for grid boxes where both the total and the 95th percentile had at least 40 years of data during this period and the data extended until at least 1999.

Source: Trenberth *et al.*, 2007.



As noted by Zolina (2012), intense precipitation in Europe exhibits complex variability and a lack of a robust spatial pattern. The changes in heavy precipitation suggested are inconsistent across studies, and are region and season specific. However, the dominating tendency for many regions, using several indices, is that heavy precipitation has been increasing. In many regions, including Central-Western Europe and European Russia, increasing trends in high percentiles of daily winter precipitation were found, but in some regions trends were decreasing. Also the structure of precipitation has changed: short and isolated rain events have been regrouped into prolonged wet spells. Precipitation totals in longer wet spells have increased.

For Lithuania and Estonia, Reckermann *et al.* (2011) have reported a slight positive trend in heavy precipitation events over the last half century, and expect these increases to continue and accelerate in the future by up to 22 %.

Modelling extreme precipitation

Precipitation in Northern Europe depends to a considerably larger extent on moisture transported from remote regions in the North Atlantic storm tracks than in Southern Europe, where precipitation relies more on regional evaporation (Trenberth *et al.*, 2003; Trenberth, 2011).

The overturning rate of the hydrological cycle is closely connected to precipitation intensity and the duration of dry spells, and has been observed to have increased in Europe in the 20th century. Model simulations, assuming climate model runs from the Coupled Model Intercomparison Project 3 (CMIP3) archive for atmospheric greenhouse gas and aerosol concentrations (Meehl *et al.*, 2007a; Solomon *et al.*, 2007; Giorgi *et al.*, 2011), indicate further increases in the 21st century. For Northern Europe, these simulations predominantly indicate higher precipitation intensity, whereas for Southern Europe, they predict increased dry spell lengths (Dai, 2011a; Giorgi *et al.*, 2011).

Regional climate model results for Northern Europe, based on eight global model simulations, imply that high intensity and extreme precipitation become more frequent in a projected scenario climate after ~70 years. The increased frequency is estimated to be larger for more extreme events, but with considerable sub-regional variations (Haugen and Iversen, 2008; Benestad, 2010).

Model simulations of cloud processes and the hydrological cycle involve aspects that are not known with high precision. Even though theory, observations and model results appear consistent, climate scenario projections are expected to change and cover a wider range of precipitation events as spatial resolution and the representation of processes and natural variability improve.

For Southern Europe, one climate model simulation indicates an annual precipitation decrease of 10–40 % at the end of the century for Portugal, depending on the scenario and region (SIAM II, 2006). The extreme precipitation indices for the end of the century have a less clear trend than for temperature. Nevertheless, the projected climate scenarios suggest an overall decrease in total precipitation and a significant increase in the length of dry spells, in particular during autumn and spring, and an increase of heavy precipitation events (Costa *et al.*, 2011).

As regards precipitation, analysis of data from the European Climate Assessment and Dataset project[8] reveals that for 1961–2006 precipitation in the Iberian Peninsula decreased on average by about 60–120 mm/year per decade with larger decreases in its northwest region. This has been accompanied by more frequent droughts, which implied a decrease in the Palmer Drought Severity Index (PDSI, see Glossary) from 1961–2000 (SIAM II, 2006; Sousa *et al.*, 2011).

It should be noted that there are considerable problems concerning observations of snowfall, since the collection efficiency of snow in rain gauges is considered to be systematically under-estimated during windy conditions. False positive trends may occur in a warming climate if precipitation systematically shifts from snowfall to rain, since the collection efficiency of rain generally is higher (Førland and I.Hanssen-Bauer, 2000).

The SREX report (IPCC, 2012), projects precipitation extremes increasing in Northern Europe while there is a decrease in number of days with light precipitation. More regional analysis for the British Isles suggests increases in precipitation extremes on both short and longer (10 day) time scales in all seasons except summer. However, the climate models in general underestimate rainfall extremes because of their coarse spatial resolution, which may also affect the projected changes for the future.

Future precipitation

It has been argued heuristically that extreme precipitation events will increase during climate change as the Earth's

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[8] http://eca.knmi.nl

surface is warmer and the height of the troposphere is lowered (Trenberth *et al.*, 2003; Giorgi *et al.*, 2011; Trenberth, 2011). The same conclusions have been drawn based on observations (Trenberth, 2011), and on climate model results (Benestad, 2007; 2010; Haugen and Iversen, 2008; Linden and Mitchell, 2009).

The heuristic argument is based on the fact that the capacity of the atmosphere to hold water vapour increases by about 7 % per degree C of temperature increase. The increase is larger for higher temperatures. If relative humidity is approximately unchanged, as sparse observations and model calculations indicate, the actual moisture content increases at the same rate. The increased atmospheric moisture feeds storms on all spatial scales with more water vapour, and if everything else is kept unchanged concerning the dynamics, precipitation should increase in total at the same rate. However, the extra precipitation also releases more latent heat of condensation in the rising air that is originally associated with the convergence of moisture into the storm. Hence the added precipitation will enhance this vertical motion and cause enhanced convergence of more moisture. This amplification is known as a positive feedback, a technical term that does not suggest that the effects are positive, and will increase the precipitation rate when it rains further beyond the 7 % increase per degree C. Furthermore, the extra surface evaporation and latent heat release aloft plays a role in the vertical energy flow and the planet's energy balance.

At the same time, higher surface temperature increases evaporation from the ground, causing intensification and increased duration of dry spells. Furthermore, models indeed predict only a total increase of 1–2 % per degree C. This implies that events with light and moderate precipitation amounts must on average decrease, while the heavy precipitation events become more frequent. This happens even in regions with decreasing total precipitation amounts (Trenberth, 2011), and Benestad *et al.* (2012a and 2012b) observed a connection between the wet-day mean and high 24-hour precipitation percentiles in more than 10 000 rain gauges over the USA, supporting the model results.

This is in agreement with the analysis of Giorgi *et al.* (2011). A three-model ensemble of high-resolution regional climate model projections shows a clear increasing trend in a normalised index describing the HY-INT for all regions, including Europe, and all models considered. The magnitude of the trends over the 21st century for Europe was significant at 5 % for all three models, respectively 0.18, 0.29, and 0.32 standard deviations per 100 years for the SRES A1B scenario used in *IPCC Fourth Assessment Report* (Solomon *et al.*, 2007). The corresponding regional trends in precipitation intensity and dry spell length for Europe are given in Table 3.1. The increasing precipitation intensity dominates over Northern Europe, while the increasing dry spell lengths dominate in the south, in agreement with the review by Dai (2011a). The increase in HY-INT is of comparable magnitude in the two sub-regions.

Giorgi *et al.* (2011) presented similar trends based on precipitation observations over the 25-year period, 1976–2000. Estimated trends were positive for HY-INT: 0.19 in Northern Europe and 0.60 in Southern Europe, but only the latter was statistically significant at the 5 % level. The increase in the index for precipitation intensity (INT) was 0.18 (significant at the 5 % level) in the north and 0.00 in the south. The trend in dry spell length (DSL) was estimated at 0.00 in the north and 0.64 (significant at the 5 % level) in the south.

Climate projections using multi-model ensembles show increases in globally averaged mean water vapour and precipitation over the 21st century. Yet, precipitation scenarios show strong inter-model, regional, and seasonal differences. In Europe, there is a marked contrast between predicted future winter and summer precipitation change. Wetter winters are expected throughout the continent except for the Mediterranean region – in many places less snow and more rain, while in summer, a strong difference in precipitation change between Northern Europe, getting wetter, and Southern Europe, getting drier, is projected (Kundzewicz *et al.*, 2006). However, various climate models do not consistently project precipitation change, disagreeing even as to the sign of change, in contrast to consistent temperature projections – ubiquitous warming in all model runs (Kundzewicz *et al.*, 2007).

Generally, intense precipitation is likely to be impacted more than the mean precipitation. In most areas, climate projections for the 21st century show increases in average annual precipitation intensity (Figure 3.7). The highest quantiles of daily precipitation amounts and annual maximum daily precipitation are anticipated to increase over many areas, also some of such areas where the mean precipitation is projected to decrease

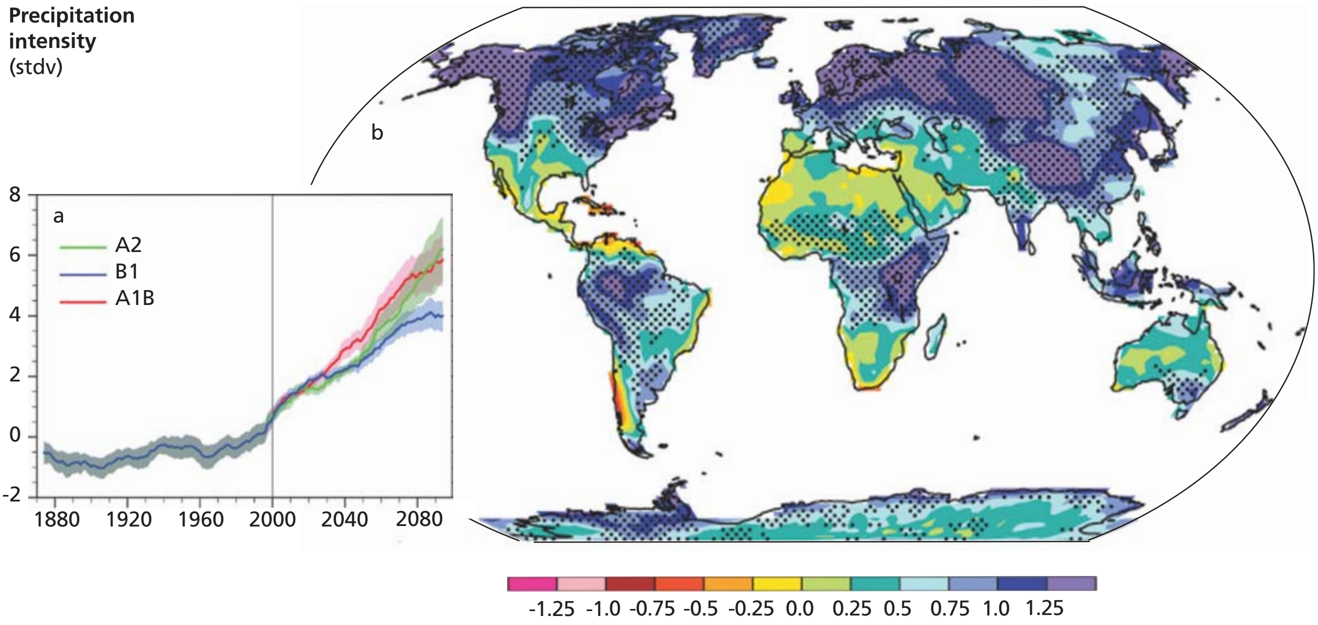


Figure 3.7 Changes in spatial patterns of precipitation intensity (defined as the annual total precipitation divided by the number of wet days) over land, based on multi-model simulations from nine global coupled climate models Inset: Globally averaged changes in precipitation intensity for a low (SRES B1), middle (SRES A1B) and high (SRES A2) scenario. Map: Changes in spatial patterns of simulated precipitation intensity between two 20-year means (2080–2099 minus 1980–1999) for the A1B scenario. Solid line in the inset is the 10-year smoothed multi-model ensemble mean; the envelope indicates the ensemble mean standard deviation. Stippling on the map denotes areas where at least five of the nine models concur in determining that the change is statistically significant. Each model's time series was centred on its 1980–1999 average and normalised (rescaled) by its standard deviation computed (after de-trending) over the period 1960–2099. The models were then aggregated into an ensemble average, both at the global and at the grid-box level. The changes are given in units of standard deviations.

Source: Meehl *et al.*, 2007b.

(Christensen and Christensen, 2002; Kundzewicz *et al.*, 2006). Frei *et al.* (2006) used six regional climate models to simulate precipitation extremes and estimate return values for the extremes. They observed in the model results a tendency for the extremes to increase north of 45° N, with a decrease in the expected time between precipitation above extreme thresholds. In the south, on the other hand, they found small changes or reduced extremes. Yet, existing climate models are not good at reproducing local climate extremes, so that projections of extreme events for future climate are highly uncertain (Orskaug *et al.*, 2011). Furthermore, the choice of bias correction method, which to some extent is subjective, will affect the estimates of extremes and future change (Gudmundsson *et al.*, 2012; Räisänen, 2012).

Regional case studies

Higher intensity of precipitation and longer dry periods are some of the consequences expected over Europe from global warming. However, regional climate model simulations also point to considerable geographic variations. The results of climate modelling for Southern and Northern Europe are shown in Table 3.1, and the scales of future precipitation events depend on complex processes that are difficult to simulate. Projected future return periods of extreme precipitation events in Central and Northern Europe are shown in Figure 3.11, which illustrates the considerable geographic variation in such predictions within Europe (Box 3.3). However, studies of recent precipitation records of Southeastern Europe (Box 3.4) show a clear signal of a generally drier climate with fewer rainy days yet higher daily precipitation volumes.

These examples of regional studies of extreme precipitation also show the level of detail now available in assessment of past and predictions of future precipitation extremes and suggest that local geographical factors will continue to be a powerful source of variation in the way in which the overall European trends will be translated into local extreme precipitation events.

BOX 3.4 PRECIPITATION EXTREMES

Several studies of projected precipitation extremes with high-resolution models show an increase in Northern Europe, especially during winter. Results from Haugen and Iversen (2008) are representative of these studies and some results are shown here to illustrate how an ensemble of eight dynamically downscaled climate model projections confirm and further manifest the results in ENSEMBLES and SREX for Northern Europe.

The eight-member ensemble is a combination of dynamically downscaled global model projections under different scenarios for greenhouse gas concentrations and aerosol emissions. The regional model used a ~50 km grid mesh width centred over Northwest Europe, and the global projections were made with five different models or model versions. The data were produced for time slices representing recent present-day climate conditions, and some assumed future development according to the scenarios. The original time slices covered different periods, and the results were scaled to the same periods: the 1961–1990 for the control climate, and a 30-year period 70 years later as the scenario climate. A simple bias-correction for systematic errors for present-day climate averaged over a central North European/North Atlantic control region. The resulting adjusted set of climate projections was used to estimate the frequency of occurrence of given thresholds, as well as values for given return periods. Recently, a set of climate model simulations by Deser *et al.* (2012) suggested that the role of natural variations in the large-scale atmospheric flow may be more important than previously anticipated on 50-year time scales. Hence one caveat with a small ensemble of eight is that it only gives a very limited impression about the plausible range of future outcomes. Moreover, ensembles should involve a large set of independent GCM simulations in order to provide a good sample of different natural states.

Table 3.1 Linear trend coefficients for precipitation intensity (INT) and dry spell length (DSL)
Both normalised with their 20th century mean value, estimated with three regional climate model projections (RCM 1, 2, and 3) for the 100-year period 2001–2100 and the A1B scenario averaged over the domains in Europe (land only). Numbers outside brackets are significant trends at the 5 % level.
Source: Giorgi *et al.*, 2011.

		INT	DSL
RCM 1	Europe	0.07	0.11
	Northern Europe	0.11	(0.00)
	Southern Europe	(0.02)	0.24
RCM 2	Europe	0.11	0.20
	Northern Europe	0.12	0.09
	Southern Europe	0.09	0.33
RCM 3	Europe	0.03	0.26
	Northern Europe	0.04	0.21
	Southern Europe	(0.02)	0.31

Figure 3.11 shows maps of estimated daily precipitation – amounts accumulated over 24 hours – for three different return periods in the control climate, and with response factors for changes in the same return periods estimated for the scenario climate after 70 years. The response factor (n) denotes the increased frequency of occurrence in the projected scenario climate after 70 years. Values larger than 1 ($n>1$) imply that the events are projected to occur n times as often in the scenario climate. Values below 1 indicate that extreme events are projected to be rarer in the scenario climate.

In all cases the response factors are predominantly higher than 1, meaning increased occurrence of the event, and the factors increase for gradually more extreme events. The highest factor for the 95th percentile of precipitation exceeds 1.25 in Northern Europe; the 1 per year occurrence has a return factor higher than 1.5 in major parts of the area, while the 1 per 5 year event will occur twice as often in many areas. There are considerable sub-regional variations.

Empirical-statistical downscaling (ESD) is computationally cheap but is in principle limited to locations where there are observations. Applying ESD, projections of the 95th

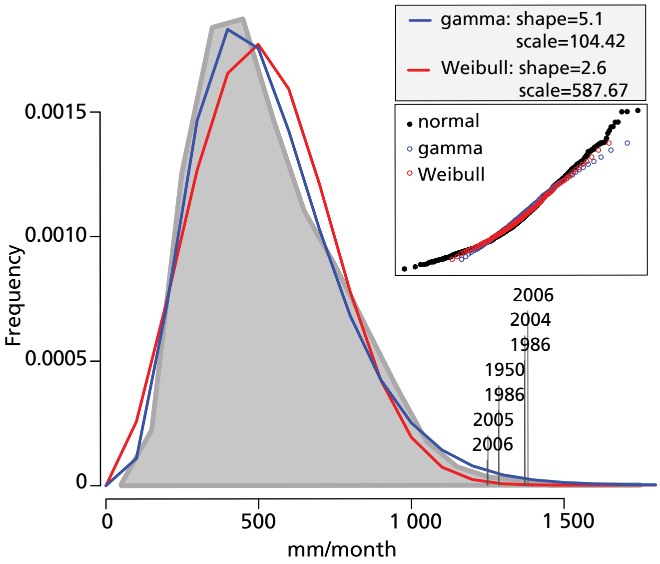
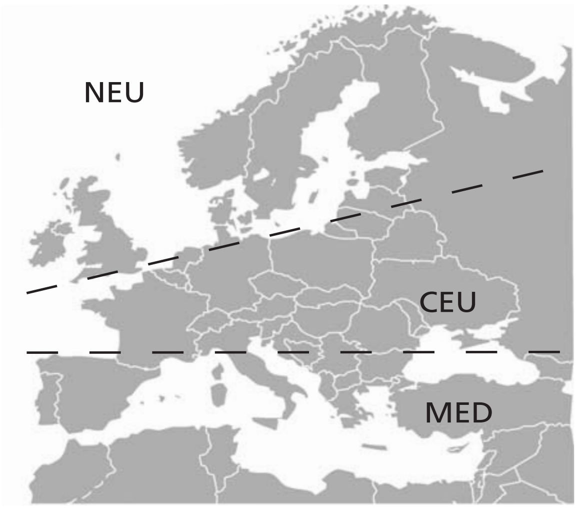


Figure 3.8 Example of an extreme precipitation amount experienced over three months in Bergen, Norway

The red curve is a Weibull distribution fitted to respective three-month periods over the years 1890–2011, and the blue curve shows the corresponding gamma distribution. The accumulated three-month precipitation amounts are given along the x-axes. The seven largest amounts are denoted with years. 2006 marks the most extreme three-month accumulation amount. The insert shows a percentile-percentile plot comparing the actual data against three theoretical distribution functions, Gaussian, gamma and Weibull, showing that the gamma distribution will underestimate the probability of occurrence of extreme events.

Figure 3.9 Definition of European regions

Source: IPCC WGII SREX, 2012.



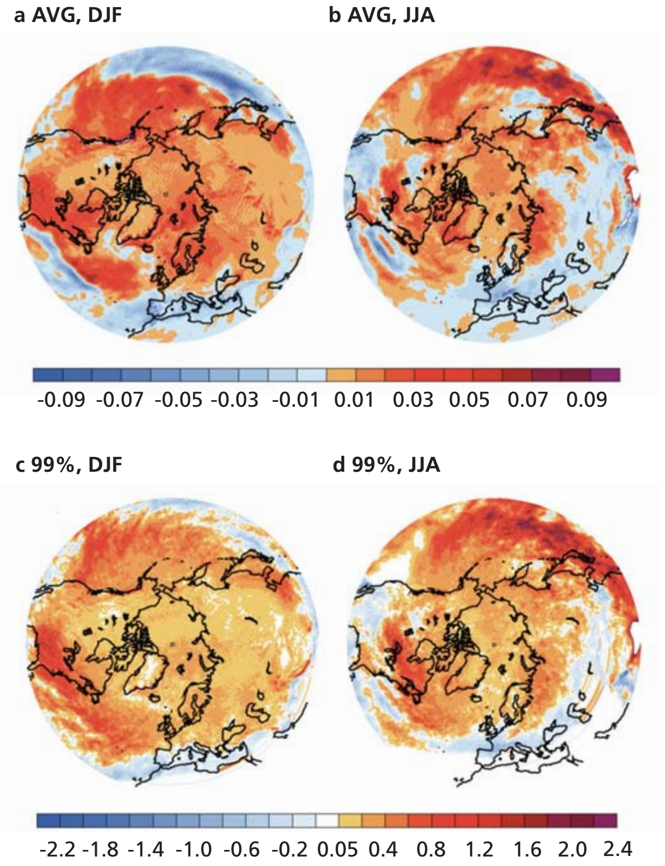


Figure 3.10 The geographical distribution of changes in average (a, b) and extreme (c, d) precipitation (mm/hr) for the northern hemisphere between the 21st century (2069–2100) and the 20th century (1959–1990)

From the ECHAM5 atmosphere model at T213 with 31 vertical levels, using IPCC scenario A1B with the time-slice method. SST and sea-ice fraction data are from one of the T63 ECHAM5OM coupled model integrations. (a) DJF time mean, (b) JJA time mean, (c) DJF 99th percentile, (d) JJA 99th percentile.

Source: www.eu-ensembles.org, ENSEMBLES final report p.9.

percentiles for 24-hour precipitation over Northern Europe can be based on relations between the mean conditions and the shape of the probability distribution (Benestad, 2007). Taking ensemble means of ESD-based temperature and precipitation over 21 different CMIP3 GCM projections for the SRES A1B scenario, suggests a general increase in the 95th percentile by roughly 10–20 % by 2050. Tentative results from the multi-model ESD estimates may suggest that trends in higher percentiles than the 95th may be stronger (Benestad, 2010). This would be in agreement with the results in Figure 3.11 (Haugen and Iversen, 2008). Note that ESD and RCMs

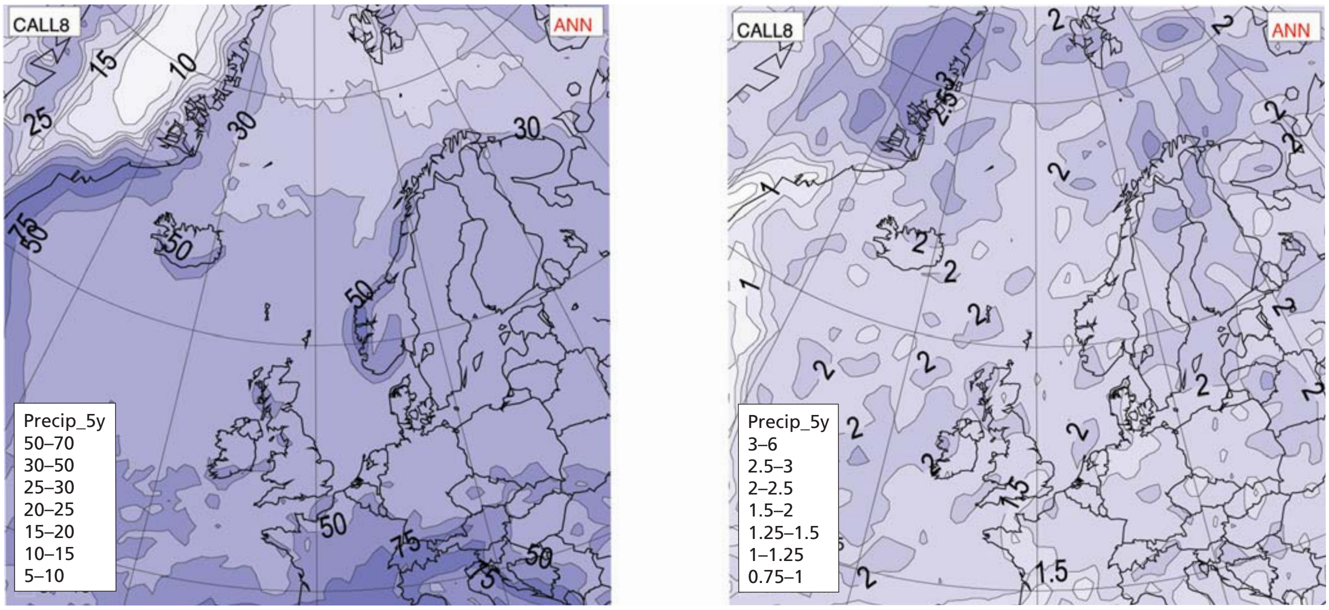


Figure 3.11 Projected climate change response factors
Left: Daily precipitation values with return periods of five years for the control climate in 1961–1990 estimated from a dynamically downscaled ensemble of eight global climate simulations. Right: Projected climate change response factors (n) in this return period for a scenario climate 70 years later, based on eight dynamically downscaled global climate projections that use different IPCC scenarios for anthropogenic forcing (IS92a, CMIP2, A1B, A2 and B2). A response factor n implies that the events occur n times as frequently in the scenario climate as in the control climate, i.e. the length of the return period is to be divided by n in the scenario climate.
Source: Haugen and Iversen, 2008.

are based on different philosophies: RCMs draw on information embedded in physical theory encoded as computer lines, whereas the source of information utilised by ESD is the observations of the climate parameter.

In conclusion, global warming will most likely affect the hydrological cycle, mainly in terms of increasing rates of evaporation associated with higher temperature. The increased evaporation will be balanced by more precipitation or the atmosphere will be subject to higher atmospheric humidity and water content. Higher water-vapour concentrations will have a strong feedback on the greenhouse forcing, whereas higher water content will affect cloudiness. The hydrological cycle also plays a role in the energy flow from the Earth's surface to higher levels aloft where heat can escape to space through the formation of clouds. Precipitation tends to take place in regions of ascending moist air, which may be associated with convective clouds, low-pressure systems along the storm tracks and frontal systems. The location and timing of these phenomena depend on the atmospheric circulation and the large-scale flow. For sub-tropical regions, such as Southern Europe, more dry days are expected with stronger subsidence associated with a shift in the large scale feature known as the Hadley cell (see Glossary). More precipitation is expected over Northern Europe, although we cannot yet project with great confidence whether the storm tracks will change. Analysis also indicates that the amounts of water falling when it rains tend to increase in a warmer world.

3.3 Storms: extreme winds

In summary,

- there is some evidence that winter wind storms over Northwestern Europe have increased over the past 60 years, with a maximum of activity in the 1990s;
- controversy remains, however, regarding longer-term changes since the middle of the 19th century, as results seem to depend on the data set used;
- under the assumption that there is no adaptation to climate change, scenario simulations for a future climate suggest an increase of damage in Northern and Central Europe, with an increase in damage of between 30 % and 100 % in Central Europe;
- in Southern Europe, it is expected that there will be fewer extreme wind storms.

BOX 3.5 EASTERN MEDITERRANEAN AND SOUTHWESTERN EUROPE

Eastern Mediterranean

A study for the Middle East (Black *et al.*, 2010) reported decreasing winter rainfall over Southern Europe and the Middle East with increased rainfall further north caused by a poleward shift of the North Atlantic storm track and a weakening of the Mediterranean storm track. Nastos and Zerefos (2007) have shown that in Athens, Greece, daily precipitation parameters, shape and scale, for the past two decades both show a significant difference compared to any previous period from the 1890s through the 1970s. Also notable changes were observed in daily precipitation totals exceeding a range of thresholds. More specifically, a negative trend in the number of wet days, notably since 1968, and a positive trend in extreme daily precipitation are evident. The changes of heavy and extreme precipitation events in this part of Southeast Europe have significant environmental consequences, causing considerable damage and loss of life. In the case of Southeast Europe, Kioutsioukis *et al.* (2010) have shown that a shift towards a drier climate over the domain, while extreme rainfall events increased in variability without following any coherent regional pattern. Changes in the precipitation extremes are associated with changes in both the scale and location of the fitted distribution. The highest range of change was found for the scale parameter for both temperature and precipitation extremes, highlighting that the factor that is most influenced is the inter-annual variability of the extremes.

Projected precipitation rates are quite variable. Annual precipitation is expected to decrease in Southern Europe – Turkey and the Levant – whereas in the Arabian Gulf it may increase. In the former region rainfall is actually expected to increase in winter, while decreasing in spring and summer, with a substantial increase of the number of dry days. In the northern part of the Eastern Mediterranean, mainly across the Balkans, Cyprus, Israel, Lebanon, and Turkey, the number of rainy days may decrease by 10–20 days per year at the end of the century. The intensity of precipitation, the maximum amount of rain per day, is expected to decrease other than over the northern Balkans and the Caucasus.

Southwestern Europe

Climate change scenarios for the 21st century in Southwestern Europe, obtained with different GCMs, suggest a strong increase in all temperature-related indices and a significant decrease in precipitation (Solomon *et al.*, 2007). Future climate projections for Portugal in 2071–2100 reveal reductions in mean annual precipitation and in the duration of the rainy season (SIAM, 2002; SIAM II, 2006) and strong projected increases in the length of dry spells, particularly in autumn and spring (Costa *et al.*, 2012). An extension of the dry season from summer to spring and autumn is very likely to occur.

The most important mechanism responsible for the strong inter-annual precipitation variability in Southwestern Europe is the North Atlantic Oscillation (NAO). GCM projections of the NAO index indicate a future general positive trend throughout the 21st century (Demuzere *et al.*, 2009). There are uncertainties in these projections since the current GCMs are unable to consistently reproduce the observed amplitudes of the inter-annual variability of the NAO indexes. Future scenarios for increasing drought and precipitation extremes reflect the projected strengthening and displacement of the Azores high-pressure system, which is related to a stronger and more frequent positive phase of the NAO index. The most extreme negative NAO index for winter was recorded in 2010 and the most extreme daily precipitation events in that year in the Iberian peninsula were recorded in the period with the strongest negative NAO index (Vicente-Serrano *et al.*, 2011). The anomalous wet 2010 winter in Iberia reflected a regional future resulting from wider anomalous conditions in the global atmospheric circulation (Cattiaux *et al.*, 2010; Wang *et al.*, 2010). Although there is a general future trend for a positive NAO index, the projections based on the GCMs also indicate extreme negative values of the NAO index, similar to those observed in the winter of 2010 (Vicente-Serrano *et al.*, 2010).

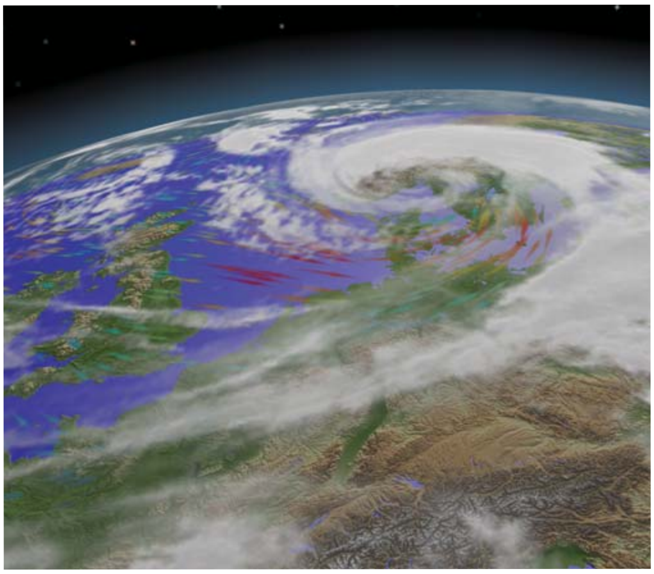


Figure 3.12 The wind storm on 3 December 1999
The coloured lines indicate the maximum wind speed.
Source: MSG2 and ECMWF ERA-40 winds.

Wind storms in Europe

European wind storms, also referred to as synoptic storms, are intense and travelling cyclones, which are associated with larger areas of low atmospheric pressure. They occur most frequently during winter months. They are connected to systems of low atmospheric pressure that travel along the so-called Atlantic storm track from North America over the North Atlantic towards the northern and central parts of Europe. Extreme wind speeds are a frequent feature on the northern coasts of Britain and Norway, but in terms of loss those hitting less frequently affected European countries are of greater concern.

Such storms cause more than half of the economic loss caused by natural disasters in Europe (Munich Re, 1999; 2007). Their comparatively high frequency, in combination with the enormous concentration of economic values in Europe, results in a loss potential comparable to earthquakes, floods and hurricanes in the USA and Japan.

Figure 3.12 shows, as an example, the severe storm named *Anatol* in Germany, *Decemberorkanen* in Denmark, and *Carolastormen* in Sweden, which hit Denmark, southwest Sweden, and northern Germany on 3 December, 1999. The storm had sustained winds of around 150 km/h and wind gusts of up to 184 km/h. This would classify it in the tropics as a category 1 hurricane.

The highest wind speeds occur over sea, along the coastal regions and in the mountain ranges (Donat *et al.*, 2011a). At the coast, there is a complex effect of extreme winds on the ocean surface. Resulting surges and waves are an additional risk for the coastal and adjacent inland areas, as is clearly evident from major events such as the 1962 Hamburg Sea Surge and the flooding of large parts of the Netherlands in 1953.

In spite of a rather dense network of meteorological stations over Europe, it is difficult to obtain homogenous wind data, at a high spatial resolution, necessary for example for potential damage assessment. Thus, reanalysis data and downscaled data from regional models are often considered in the analysis of storms and wind speeds.

In addition to the general definition of a European wind storm, it has been helpful in some parts of Europe to have a formal definition for the purpose of issuing severe-weather warnings or for insurance purposes. The Beaufort scale is widely recognised and is used to define levels of wind throughout Europe. In Germany, for example, wind speeds equal to or higher than Beaufort force 8 – sustained wind speeds > 17.2 m/s – define a wind storm according to insurance regulations. This value is approximately equivalent to the 98th percentile of wind speed over the plains in northern Germany (Klawa and Ulbrich, 2003).

Physical processes leading to wind storms

As mentioned above, large-scale European winter storms are a phenomenon related to the Atlantic storm track (Figure 3.13). This is characterised by moving low and high-pressure systems at the surface and associated troughs and ridges in the upper troposphere. Europe finds itself geographically downstream of the maximum of the Atlantic storm track located over Newfoundland.

Although some of the cyclones that affect Europe originate over North America, those producing extreme wind over Europe usually have an intensification phase over Europe, produce a secondary low-pressure system in this area or are even generated close to the continent, for example Genoa cyclones. In either case, large pressure gradients occur, mostly south of the core's track, and lead to strong winds. Under particular conditions, such as a strong meridional temperature gradient, related to the concept of baroclinicity or a high latent heat content, some cyclones may develop into severe storms.

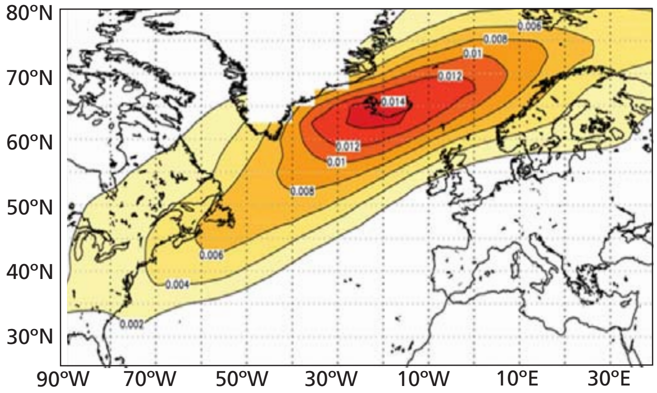


Figure 3.13 Track density (cyclone days/winter) of extreme cyclones over the North Atlantic and Europe Derived from the NCEP-reanalysis (1958–1998).
Source: After Pinto *et al.*, 2009.

Wind gusts that significantly exceed the mean wind speeds are the phenomenon that actually produces the damage in a wind-storm field. As they are neither well resolved in observations, due to the limited density of the network, or in weather forecasts, due to models' restrictions in terms of resolution and simplifications of the numerically solved equations, alternative approaches for estimating gust intensities have been developed, basically by assuming that wind energy from higher levels is transported downward to the surface.

The frequency of wind storms is associated with the North Atlantic Oscillation (NAO), which can be quantified from the pressure differences between stations in Iceland and Portugal. A high NAO index indicates low pressure over Iceland and high pressure over Southwestern Europe, leading to enhanced, or geostrophic, winds and an increased frequency of wind storms over Central Europe. While the likelihood of wind storms is highest at very high values of the NAO index, which rarely occur, the maximum in storm frequency occurs in the more frequent moderately positive phases of the NAO (Donat *et al.*, 2009; Pinto *et al.*, 2009). There are also storm occurrences, however, during the negative NAO phase. Physically, the relationship with the NAO can be understood from the fact that a strong NAO contributes to an enhanced westerly mean flow over the Eastern Atlantic and the European continent, adding to the mostly westerly winds in the storms themselves, and enhanced meridional temperature gradients (Pinto *et al.*, 2011). Accordingly, the seasonal distribution of the number of European winter storms shows a maximum when the meridional temperature gradient between the North Pole and the Equator is largest.

Recent variability of wind storms

The past 60 years have been characterised by an increase in European storminess, with a strong increase from the 1960s to the 1990s and a decline thereafter. The extent to which this is part of natural variability or related to anthropogenic climate change is not known and needs further investigation. Long-term changes in European storminess are not yet clear as studies taken as a whole are inconclusive, with sometimes conflicting results.

Keeping in mind the caveat associated with the 20CR data, Wang *et al.* (2012) also found a long-term decline in storminess for the North Sea region, and increases in spring and summer cyclone activity in the high-latitude North Atlantic associated with a lengthening of the storms' lifespan. In summer, the lengthened storm lifespan was accompanied by a decrease in storm counts. Wang *et al.* also found increases in both count and lifespan of storms during winter and autumn over Northern Europe. They noted further that trends in cyclone activity appeared to be consistent with reported changes in precipitation characteristics, such as frequency, intensity and length of wet spells. The cyclone and storm statistics over the Mediterranean region has differed to that of Northern Europe, and an increase in the mean storm intensity and lifespan during autumn seems to have been accompanied by a decrease in the number of storms. During winter, there has, according to Wang *et al.* (2012), been a tendency towards slightly shorter mean life span and decrease in storm count. For Central and Northeastern Europe, their analysis suggests that there have been increases in the mean intensity and lifespan of winter cyclones, as well as an increase in the number of autumn cyclones.

While studies using wind proxies derived from pressure observations generally emphasise a strong multi-decadal variability (Alexandersson *et al.*, 2000; Bärring and von Storch, 2004; Wang *et al.*, 2009), recent studies of extreme wind speeds in a new centennial-scale physical reanalysis find significant upward trends in Central, Northern and Western Europe (Donat *et al.*, 2011b; Bronnimann *et al.*, 2012). For the North Sea area, for example, the time-series based on the different data sets agree well for the past 90 years, but show larger differences before 1920 (Figure 3.14). This may partly be explained by the increasing incorporation of observational data in the early time

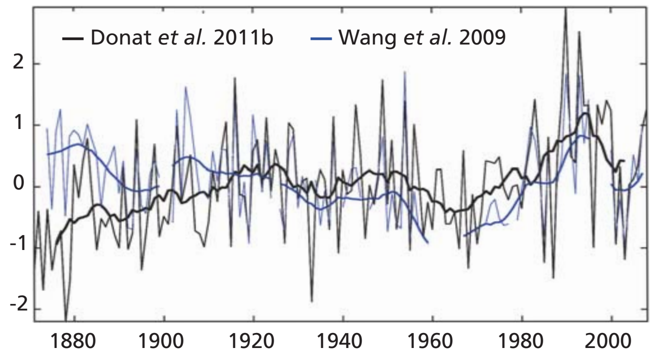


Figure 3.14 Time series of the standardised annual 95th percentile of wind speeds over the North Sea area

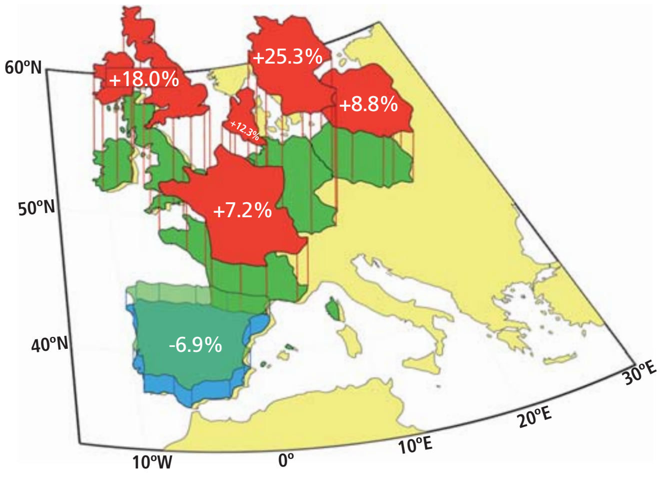
Source: data from Wang *et al.*, 2009; Donat *et al.*, 2011b.

period of this dataset, leading to inhomogeneities and thus inconsistency in trends (Krueger *et al.*, 2012). However, Wang *et al.* (2012) find good agreement of storm statistics from this long-term reanalysis and observations for the North Atlantic-European region, as do Bronnimann *et al.* (2012) for wind speeds in Central Europe. Note that observational studies also show upward trends in the North Sea region if only the winter season is considered (Wang *et al.*, 2009), while they also suggest that strong storminess about 100 years ago seems to have occurred during summer months – a phenomenon that still needs to be meteorologically understood. It is the winter storms that tend to cause the most damage and greatest economic loss.

Figure 3.15 Relative changes (%) of mean annual storm loss potential

Based on 9 GCM and 14 RCM simulations for the end of the 21st century (2071– 2100) compared to recent climate conditions (1961–2000)

Source: after Donat *et al.*, 2011a.



The insurance industry reports a strong increase in storm damage during recent decades but this does not imply that storminess is increasing (Ulbrich *et al.*, 2009) as industry data show that it can largely be attributed to inflation, increasing wealth and economic values (Barredo, 2010), and is further affected by changes in vulnerability. A more suitable parameter for the quantification of wind-storm damage is the loss ratio, that is the relation of total loss and total insured values, as it normalises the effect of inflation. Several studies have been published assessing the relation of loss ratios and wind speeds based on these insurance data and on observed wind speed data. The approach of estimating the loss ratio from the cube of normalised wind speed in excess of the threshold of the local 98th percentile has proven to give a rather good estimation of the annual loss in different regions of Western and Central Europe, for example in the United Kingdom and Germany (Leckebusch *et al.*, 2007; Donat *et al.*, 2010).

In general, an increase of storm loss potential of up to 38 % is found for Central Europe (Figure 3.15, Donat *et al.*, 2010). Not unexpectedly, storm-surge damage estimates also show a significant rise in the same region (Gaslikova *et al.*, 2011). There is, however, a decreased storm risk in Southern Europe. One has, however, to bear in mind that natural variability on the decadal time scale plays a significant role in these estimates, and that the standard deviation between changes in the individual model runs is as large as the average increase (Donat *et al.*, 2010).

Future wind storm scenarios

Under the increasing greenhouse gas concentrations of the IPCC SRES scenarios, climate models project a decrease in the total number of cyclones in the northern hemisphere mid-latitudes. However, these models indicate an increase in the number of severe storms in Northwestern and Central Europe, which is also in accordance with the PRUDENCE results (Beniston *et al.*, 2007). The simulations also suggest a significant increase in cyclone intensity and the number of intense cyclones over Northwest Europe. Connected to the increase in storm intensity, wind speeds over Central and Western Europe will increase under future climate conditions (Leckebusch *et al.*, 2006, 2008; Pinto *et al.*, 2009; Ulbrich *et al.*, 2009). A belt stretching from the United Kingdom to Poland will experience an increase in extreme wind speed (Figure 3.16), while Southern Europe and the Mediterranean will rather see a decrease in strong winds (Leckebusch *et al.*, 2006; Donat *et al.*, 2011a).

Harvey *et al.* (2012) noted that while new global climate models (CMIP5) have higher spatial resolution, incorporate a description of the stratosphere and have an improved description of Arctic sea-ice, they tend to provide a similar picture of storm tracks as the older generation of the models (CMIP3) in many respects. There are, however, important differences, as the more recent generation of GCMs do not give a clear indication of a polar shift of the storm tracks, and there are different responses in the storm activity to global warming in the vicinity of the sea-ice edge. Furthermore, the projected response of storm activity to global warming was found to be of the same order of magnitude as natural year-to-year variations (inter-decadal or inter-annual). However, the response could vary amongst the different models and different locations.

3.4 Convective events: heavy rain storms/wind storms

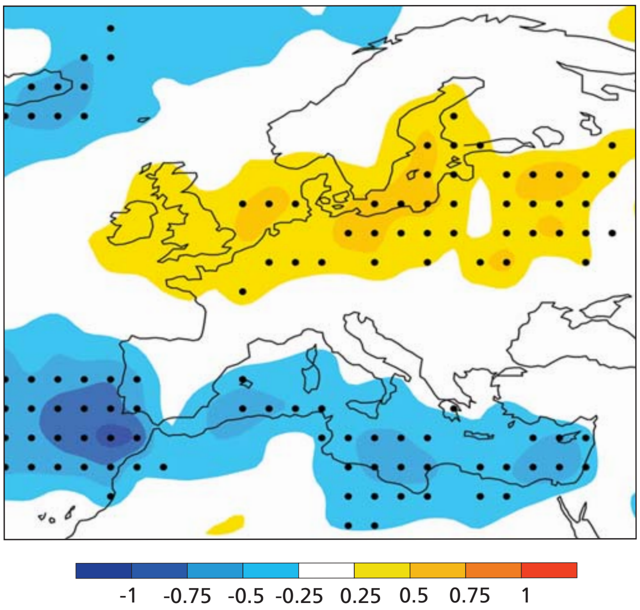
In summary:

- The data available for convective, summer storms is not sufficiently harmonised at present to provide a reliable assessment of recent trends.

Figure 3.16 Ensemble mean of the 98th percentile of the maximum wind speed in the climate model simulations

Shown are the changes for the IPCC-SRES-scenario A1B for 2071–2100 relative to 1961–2000. Coloured areas indicate the magnitude of change (m/s), statistical significance above 0.95 is shown by black dots (significance as assessed by Student's t-test).

Source: Donat *et al.*, 2011a.



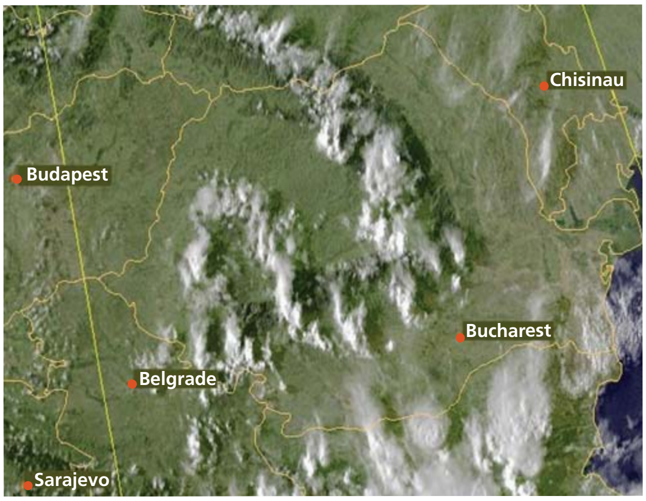


Figure 3.17 Convective storm over Romania

During the afternoon, the convective storms over the mountains trigger lines of thunderstorms that move into the Danube valley.

Source: http://www.eumetsat.int/website/home/Images/ImageLibrary/DAT_IL_12_05_10.html.

- However, scenario analysis suggests that in future there will be more occasions when conditions are favourable to the development of convective storms.

Origins of convective events in Europe

Severe convective storms (Figure 3.17), which are heavy rain producers and can be accompanied by hazardous wind phenomena during storm development, are extreme manifestations of moist atmospheric convection. Atmospheric convection is a basic mechanism for the vertical transport of heat, humidity and momentum from the boundary layer throughout the troposphere. The moist lower troposphere, the vertical instability of a deep atmospheric layer and the initiation mechanism for updraft formation are the basic ingredients for the development of the deep convective clouds morphologically classified as the cumulonimbus genera. Such clouds can form convective storms, which may have different horizontal and vertical extent and updraft speed. Deep and severe convective storms at mid-latitudes extend to the tropopause and can overshoot up to the lower stratosphere. The term thunderstorm is used as an equivalent to the more general term convective storm, as lightning and thunder often accompany the storm development.

Three basic types of convective storms can be distinguished (Doswell, 2001). The ordinary cell consists of a single main updraft that is usually quickly replaced by a downdraft once precipitation begins; its lifetime is typically 30–50 minutes. In most cases severe weather phenomena do not occur during ordinary cell evolution, however, they are significant as primary units of more complex multi-cell convective storms. There are then two types of severe convective storms, which are termed multi-cell and super-cell storms and which differ significantly in storm dynamics and internal organisation. Such storms can be many tens of kilometres in diameter and lines or zones of such storms can extend for hundreds of kilometres.

A multi-cell storm is usually composed of a compact cluster of single ordinary cells in different stages of development. New cells are generated by lifting at the leading edge of the cold outflow that was produced by the previous cells. The lifetime of the multi-cellular cluster can be up to several hours, which is significantly longer than the life-cycle of any individual cell. Multi-cells can have a different degree of organisation, from more or less chaotic cell clusters to highly organised linear systems as squall lines. Multi-cell storms, which are frequent in Europe, can produce heavy rain, hail and strong wind gusts – a storm that caused local flash flooding over the northeast part of the Czech Republic is an example of a strongly organised multi-cell convection storm (Rezacova and Sokol, 2003). The convective system occurred in July 1998 and had the form of a small, nearly steady squall line that persisted for about 12 hours. The recorded maximum daily precipitation reached 204 mm.

Super-cell storms develop as single vigorous cells with a pronounced rotation in their updraft regions. They usually form in an environment with strong vertical wind shear, may last for several hours and are often accompanied by severe weather, such as high winds, large hail and tornadoes. Although relatively rare in Europe, several pronounced super-cell events are reported every year and have been documented, for instance, in studies from Italy (Bertato *et al.*, 2003; Giaiotti and Stel, 2007), Austria (Schneider *et al.*, 2008) and Hungary (Horvath *et al.*, 2007).

Apart from isolated storms, mesoscale convective systems (MCS) can occur as an ensemble of multi- and super-cell storms covering an area of 100 km or more (Doswell, 2001). A particularly large and vigorous MCS, defined from the properties of the cloud shield as revealed by satellite infrared imagery, is referred to as a mesoscale convective complex (MCC). Convective systems can transform during their development, as in the case, for example, of one of the best-known severe storms in Europe, known as the Munich hailstorm in Germany, which occurred on 12 and 13 July 1984 (Höller and Reinhardt, 1986; Kaspar *et al.*, 2009). In the organised convective system with multi-cellular features, the most intense convective cells had the characteristics of a super-cell storm. The system evolved into an MCC and the damaging weather affected a strip of land from Switzerland to Poland.

The severe storm, which occurred on 2 November 2008 in Catalonia, represents a more contemporary example of complex storm development. A number of multi-cell storms, and others exhibiting super-cell features, clustered into an MCS. The storm moved northeastwards across Catalonia and produced strong and damaging wind gusts near the ground. It spawned a tornado with the potential to produce considerable damage, hail and heavy rainfall. In its later development, it also affected southeast France causing large hail, ground-level damaging wind gusts and heavy rainfall (Bech *et al.*, 2011).

Severe convective phenomena

The strong internal organisation of severe convective storms causes several types of extreme hazardous phenomena that may occur during storm development. These are heavy local rainfalls that can lead to flash flooding, large hail causing local but pronounced damage to crops and property and strong winds and wind gusts sometimes in the form of a tornado or downburst (Doswell, 2001).

According to the common definition, heavy convective precipitation can be characterised as either intense rain falling in such amounts that significant damage is caused, or the damage is unknown but the precipitation amounts observed are exceptional for the region in question. Heavy rainfall with local rainfall values of the order 10–100 mm and last for several tens of minutes can repeat itself over a given location. Such heavy rainfall may strike areas with an horizontal extent of the order of 1–10 km. Hazardous convective precipitation can be in the form of large hail, hailstones with a diameter of 2 cm or more, and/or falling smaller hailstones that can accumulate in layers of 2 cm or more.

Strong winds, wind gusts, and wind vortices are typical of severe storms. A severe wind gust is an event with wind speeds greater than 25 m/s, or one that results in damage associated with wind speeds greater than 25 m/s. Tornadoes may sometimes occur during storm development. A tornado is a violently rotating vortex a few metres to a few kilometres in diameter, extending between, and in contact with, a convective cloud and the Earth's surface. It is visible because of condensation of water vapour and/or by material that has been lifted from the Earth's surface. The vortex is strong enough to cause a material damage. A tornado-like feature forming over water is called a waterspout. There are many case studies documenting tornados all over Europe – results from a survey on average tornadic activity in Europe were published in Dotzek (2003). The survey was conducted among the participants of the European Conference on Severe Storms, 2002. The paper shows that there are 169±9 tornadoes over land per year, based on historical and recent observations. More than twice as many cases, 304±25, are estimated as an expected true climatological number, accounting for under-reporting of events in many European countries. The corresponding numbers of waterspouts are 160±3 for observations and 393±11 for estimates. For comparison, 1 170 tornadoes over land are observed in average per year in the USA (Dotzek, 2003). It has to be emphasised that tornadoes were not classified according to their intensity in the survey.

A downburst is another wind phenomenon that may occur in a severe storm. It is characterised by strong and often damaging winds from one or more convective downdrafts over a limited area, and can be accompanied by intense rain or hail. The downbursts are referred to as macro- or micro-bursts. The latter covers an area of less than 4 km along one side with peak winds that last 2–5 minutes, while the former covers an area of more than 4 km in diameter and has a typical duration is 5–30 minutes. Downbursts are a serious hazard to aircraft, especially during takeoff and landing, because of the large and abrupt changes in the vertical wind speed and direction near the ground. Widespread convectively induced straight-line wind storms can develop as a family of downbursts produced by meso-scale extra-tropical convective systems. There are numerous case studies reporting downburst, for example, the study by Pistotnik *et al.* (2011) describes a strong downburst in a sparsely populated area near Braunau, Austria during the late winter cyclone Emma on 1 March 2008, with damage indicators confirming maximum wind speeds of 61–70m/s (219–254 km/h). The study says that the assessment of this case would have had a significantly different outcome without the accomplishment of this site survey. The downburst climatology in Germany and the potential of polarimetric radar nowcasting algorithms for downburst detection were studied during the VERTIKATOR observation period in June and July 2002 (Dotzek and Friedrich, 2009).

BOX 3.6 DERECHO

A phenomenon known as *derecho* caused widespread damage in the eastern part of the USA on 29 June 2012. A line of thunderstorms stretched over 1 000 km with wind speeds near 100 km/h (*Physics Today*, 2012). Such phenomena are less common in Europe, although a similar event occurred on 10 July 2002 in Germany where a serial *derecho* killed eight and injured 39 people near Berlin (Gatzen, 2004).

The detection of convective phenomena

Severe convective storms can be detected by meteorological radar networks in combination with satellite observations and precipitation measurements. Damaging convective phenomena of a local nature can only be identified through the damage they cause, or by eyewitness reports prepared in dialogue with a meteorologist. There are local databases in many European countries which include materials about past hazardous weather events and reports with relevant meteorological data from the time period of meteorological measurement (Holzer, 2001; Webb *et al.*, 2001; Dobrovolný and Brázdil, 2003; Setvák *et al.*, 2003; Holden and Wright, 2004; Gayà, 2011). Such studies show that the occurrence of severe convective phenomena such as tornadoes in the European region is not exceptional. The climatological studies do, however, indicate an increase in reports of hazardous convective events but this increase could be related to recent increased awareness due to many more information sources and the significantly higher quality and extent of remote sensing techniques (Dobrovolný and Brázdil, 2003). The short duration, variable intensity and limited area affected by hazardous convective phenomena make it difficult to detect them even today.

At the European Severe Storm Laboratory (ESSL) several thousand reports are added to the European Severe Weather Database (ESWD) each year. In 2011, 997

BOX 3.7 EUROPEAN SEVERE WEATHER DATABASE

Despite the initiatives by individuals and organisations, including some national weather services, the collection and storage of data has not been done uniformly or consistently. To overcome this situation, European Severe Weather Database (ESWD) has been operated and extended by the European Severe Storm Laboratory (ESSL). The ESSL was founded in 2002 as an informal network of scientists from all over Europe, and formally established in 2006 as a non-profit research organisation (Dotzek *et al.*, 2009).

The ESWD collaborates with national hydro-meteorological services, voluntary observers and observer networks from European countries to collect reports about the occurrence of several categories of extreme convective phenomena.

Data samples can be retrieved by all visitors from http://www.eswd.eu; larger data sets are provided under the user registration and agreement.

reports of large hail occurrence were confirmed and 41 of them fully verified. In the same time period there were 1 604 heavy rain reports confirmed and 32 fully verified. The confirmed reports of tornado occurrence numbered 179, and seven events were fully verified. Similarly 2 186 reports of wind gusts were accepted as confirmed, 11 of them fully verified (Figure 3.18).

Dotzek *et al.* (2009) summarised how the ESWD has been used by researchers for forecast verification and climatologic studies, and by groups who seek to find ways to detect severe weather in an automatic way using satellite and radar data, thereby needing ground-truth observations. In addition, the ESSL proposed a new wind-speed scale, the Energy- or E-scale, which is linked to physical quantities and can be calibrated. Even without the presence of any physical trends, we can expect a significantly augmented ESWD database to appear in the next few years. The climatological significance of the data is therefore increasing rapidly.

Conditions that give rise to convective storms

The larger-scale conditions necessary for the formation of severe convective storms include an initiating mechanism and moist buoyant air in the atmospheric boundary layer, which is able to form vigorous updrafts in deep unstable environments. The region of summer cold fronts represents a typical European environment where severe convective storms develop. Severe storm forecasting can be carried out by identification of the larger-scale environment favourable for severe storm development (Doswell *et al.*, 1996). Two basic quantitative measures that characterise thunderstorm environments are the convective available potential energy (CAPE) and the magnitude of the vector wind difference between the surface and 6 km, S06 (Trapp *et al.*, 2007). CAPE is a measure of the vertically integrated buoyant energy available to the storm. Strong updrafts occur in environments of large CAPE which are able to support the growth of large hailstones and otherwise produce large rainfall rates, which can lead to intense downdrafts and outflow winds. The S06 quantifies the vertical change or shear in the environmental horizontal wind vector. The shear promotes storm-scale rotation about a vertical axis and also helps sustain a deep updraft in the presence of a precipitation-driven downdraft and associated thunderstorm outflow. Consequently, severe thunderstorms occur most readily when CAPE and vertical wind shear are both large in a local environment. The number of days on which the product of CAPE and S06 locally exceeds an empirical threshold has been used to discriminate environments of significant severe thunderstorms from those of all other thunderstorms (Brooks *et al.*, 2003).

Many other thermodynamic and dynamic parameters, and combinations of them, have been tested for their correlation with tornado and other extreme phenomena occurrence. In addition to CAPE and S06, the convective inhibition energy, the mid-tropospheric lapse rate, the lower-tropospheric moisture content and the storm relative helicity for different layers (Romero *et al.*, 2007) have been assessed. It has been found that S01 – the wind shear between the surface and 1 km elevation – and the height of the lifting condensation level are particularly relevant in the assessment of tornado occurrence in Europe as well as in the USA (Grünwald and Brooks, 2011).

There are two basic methodologies in the use of environment measures to analyse the occurrence of thunderstorm. In the first approach, the diagnostic measures are investigated against observations of severe phenomena in order to evaluate the climatology and predictive significance of the measures. Brooks (2009) used proximity soundings based on NCAR/NCEP data bases and the ESWD data to show that probabilities of significant severe storms are higher for high CAPE and shear in Europe, but such large-scale environmental conditions are experienced much more frequently in the USA.

The studies of the second type apply thunderstorm environment measures to the output of global climate models in order to assess the trends in severe convective storm frequency (Trapp *et al.*, 2007 for US territory; Marsh *et al.*, 2009 for Europe). Marsh *et al.* (2009) applied both approaches. Seasonal cycles of parameters conducive for the development of severe thunderstorms were computed using 20 years of output from the community climate system model v3 (CCSM3) for both a 20th and a 21st century simulation. These parameters were compared with parameters calculated from the NCEP/NCAR global reanalysis data (Figure 3.19).

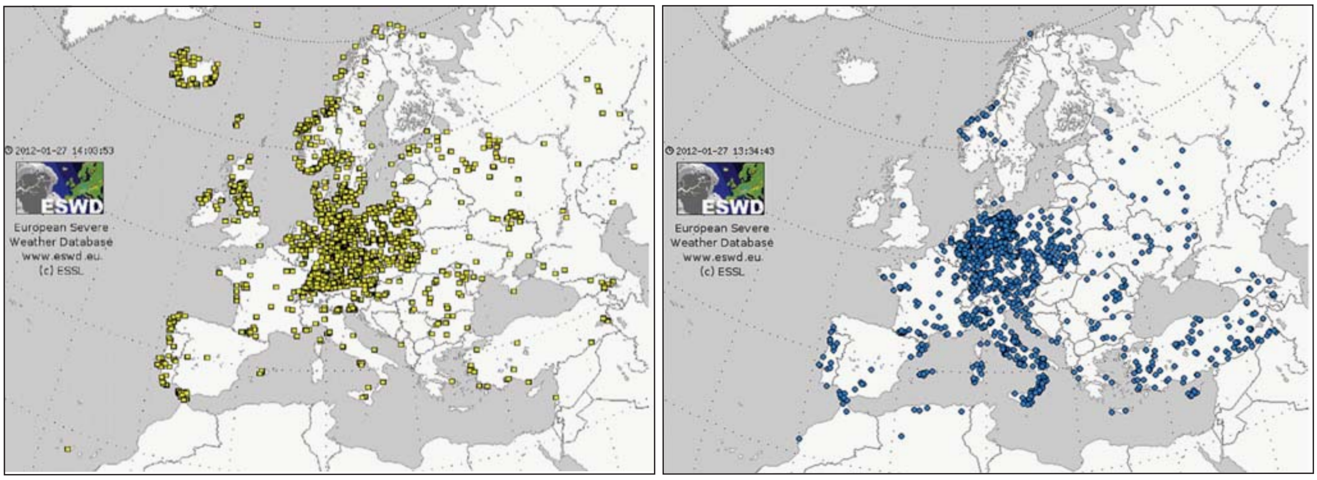
The implications of changes in the conditions such as CAPE are changes in the frequency of occurrence of convective events. Convective activity is highest during the summer season with highest CAPE, as shown in Figure 3.19, and this is also the season for which the projections indicate as being even more favourable for convective storms. There are also higher values of CAPE over the Mediterranean Sea during September–November. The increase may be strongest over parts of the Mediterranean Sea and Central Europe. There

Figure 3.18 Distribution of ESWD reports for events occurring between 0000h GMT/UTC, 1 January 2011 and 2400h GMT/UTC, 31 December 2011

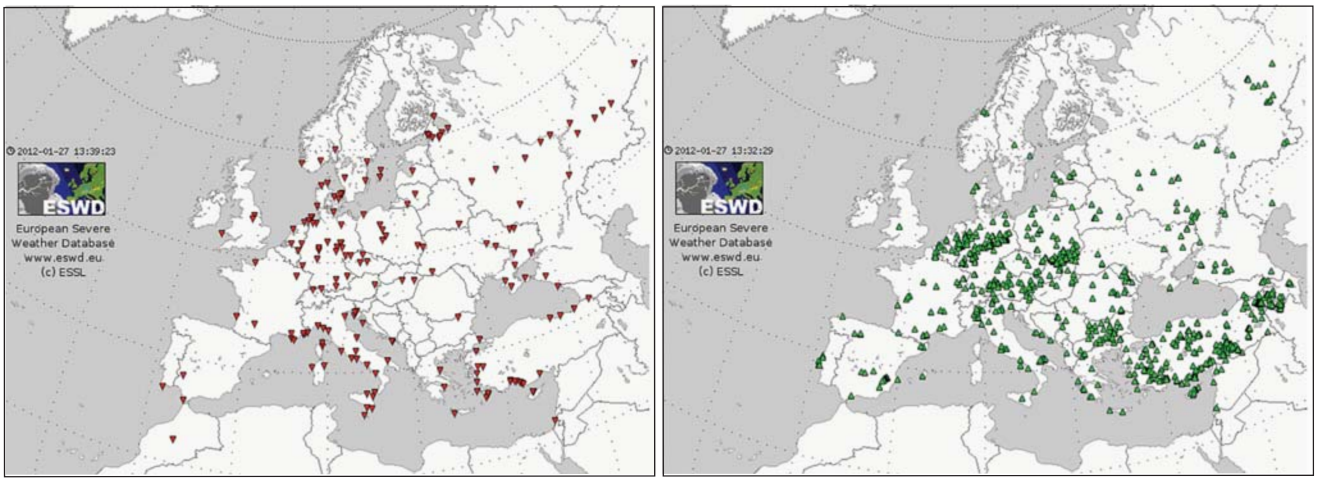
Only confirmed and fully verified reports are included.

Source: adapted from ESWD database, http://www.essl.org/cgi-bin/eswd/eswd.cgi.

Severe storm gusts **Heavy rain**



Tornadoes **Hail**



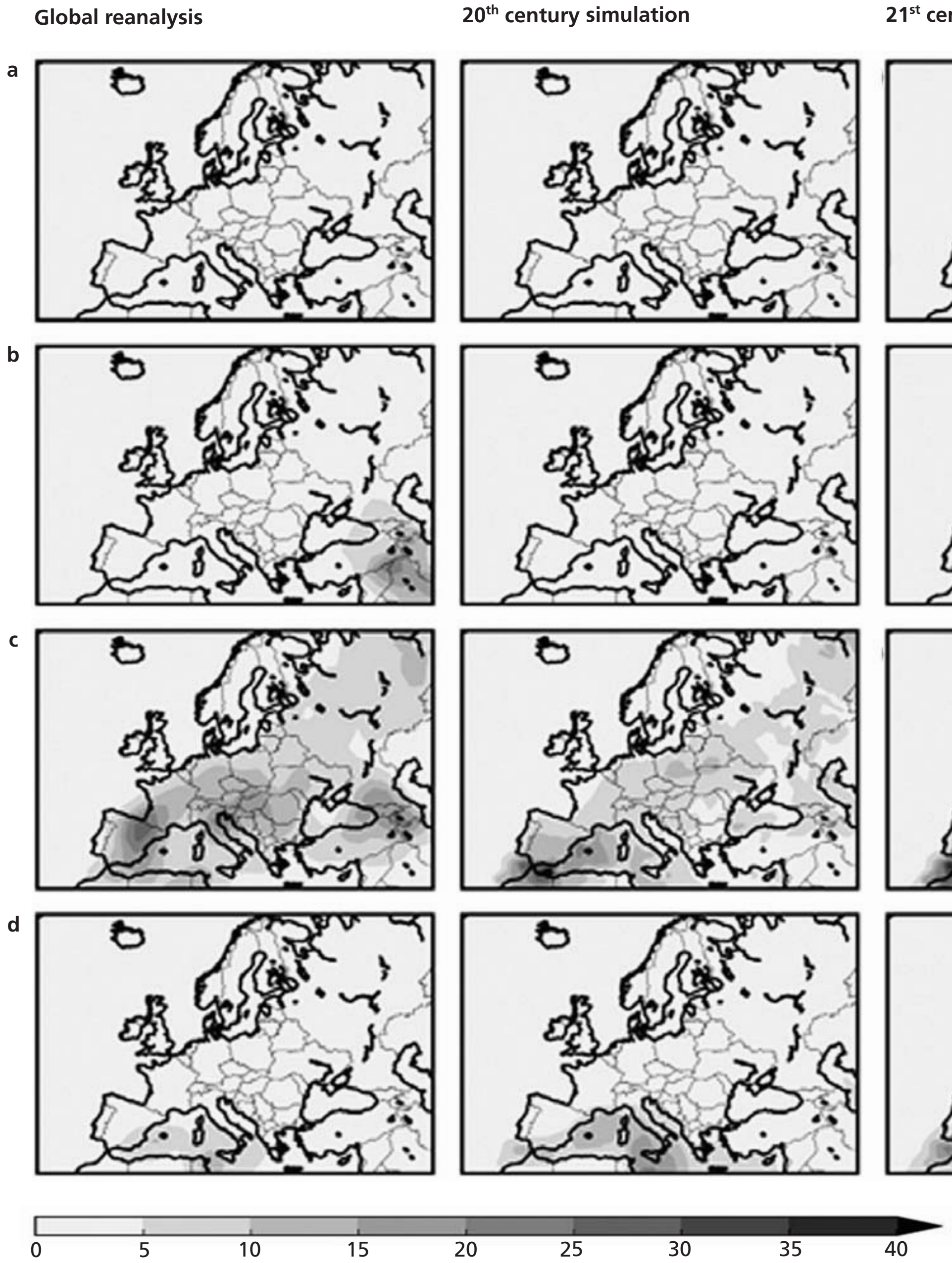


Figure 3.19 Spatial distribution of the number of environments favourable for severe thunderstorms
a: December through February; b: March through May; c: June through August; d: September through November. The values were calculated from reanalysis (left column), 20th century simulation (middle column), 21st century simulation (right column). CAPE values of 0 were included in these calculations.
Source: adapted from Marsh *et al.*, 2009.

may be an increase in CAPE during the autumn season over the Mediterranean, which are expected to lead to increased frequency of convective storms. It is also plausible that their intensity will increase with higher moisture contents (Trenberth *et al.*, 2011).

The results of these modelling experiments indicate that the CCSM3's current simulation produced distributions of both mean CAPE and favourable severe environments that were qualitatively similar to the NCEP/NCAR global reanalysis, although the CCSM3 underestimates the frequency of severe thunderstorm environments. Preliminary comparisons of the CCSM3 21st century simulation under the IPCC A2 emissions scenario to the 20th century simulation indicated a slight increase in mean CAPE in the cool season and a slight decrease in the warm season, and little change in mean wind shear. However, there was a small increase in favourable severe environments for most locations resulting from an increase in the joint occurrence of high CAPE and high deep-layer shear. Regions near the Mediterranean Sea experienced the biggest increase in both mean CAPE and favourable severe environments, regions near the Faroe Islands experienced an increase only in seasonal mean CAPE, and regions across Northern Europe experienced little change. The authors stress that one drawback to using the favourable severe environment calculation is that it says nothing about whether or not a specific condition spawned thunderstorms. This lack of information about thunderstorm initiation prevents one from making an unqualified claim about what will happen to the number of severe thunderstorms. At best, it can be said that the CCSM3 predicts that the number of occasions on which favourable severe environments develop will increase in a future characterised by anthropogenic warming.

The Swedish Rossby Centre observes that the topic of extreme rainfall is complicated by rainfall properties being strongly dependent on the time-scale studied[9]. Recent work, based on analysis of German precipitation data, suggests that convective precipitation responds much more sensitively to temperature increases than stratiform precipitation (Berg *et al.*, 2013), and that the convective events will increasingly dominate the nature of extreme precipitation with higher temperature.

Analyses of the thunderstorm environment, however, provide little information about how and whether deep convective clouds form initially. Furthermore the environmental parameters fail to predict storm morphology and the likelihood of specific convective phenomena. According to Brooks (2009), convection-resolving numerical simulations initialised by reanalysis or general circulation models could relate thunderstorm initiation to large-scale environmental conditions in different locations and times. It implies that high-resolution dynamical downscaling could be used as a means to simulate the regional climatology and variability of hazardous convective-scale weather. The study by Trapp *et al.* (2010), which used the technique of dynamical downscaling to compile the storm occurrence statistics over a large portion of the USA, supports this idea.

Until such new modelling approaches can be developed, however, it seems that the best that can be said about the future of severe convective events is that, in a warmer world, there will be more occasions when conditions are favourable to their initiation.

3.5 Other convective events: changes in patterns of lightning and hailstorms

In addition to high winds and heavy rainfall, there are other phenomena arising from extreme convective events and some of these are highly destructive. In particular, lightning is responsible for damage to electricity distributions systems and hail causes loss of valuable crops.

Present lightning detection technologies comprise ground-based detection networks and satellite-based observations. Ground-based lightning detection systems are the basic tool for lightning detection in Europe. One of the international lightning detection networks is the Central European Lightning Detection Network (CELDN), which consists of approximately 140 sensors in 19 countries (Novák and Kyznarová, 2011). Over the last decade, a new lightning detection network LINET was built across Central Europe which currently consists of more than 100 sensors and covers most of Europe (Betz *et al.*, 2009). Lightning detection systems have already gained a strong position in European weather services for use in severe weather nowcasting and warnings.

Williams *et al.* (2005) studied satellite observations of lightning flash rate and surface station observations in order to improve understanding of the response of the updraft and lightning activity to temperature in the tropical atmosphere. The tropical and mid-latitude results show that cloud-base height is a key determinant of updraft kinetic energy in thunderstorms. Outside the tropics, an elevated cloud base height may enable larger cloud water concentrations in the mixed phase region, a favourable condition for the positive charging of large ice particles.

Reeve and Toumi (1999) analysed the satellite data gathered by an optical transient detector (OTD) lightning sensor from May 1995 to February 1998. They observed that the global monthly land lightning activity, as measured by the OTD, correlated with global monthly land wet-bulb temperatures (see Glossary). The correlations were statistically significant on a global scale and they were found to improve with increasing land-area to sea-area ratio. The tropical region was found to exhibit no correlation, which corresponds to the results by Williams *et al.*, 2005). They also estimated that a 1° C

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[9] http://eca.knmi.nl

change in the average land wet-bulb temperature of the globe will result in a ~40±14 % change in lightning activity, and that the strongest response would be outside the tropics.

Hail is the second phenomenon with significant impacts in Europe. Hail forms as ice balls or irregular lumps of ice, which, by convention, have equivalent diameters of 5 mm or more. Smaller particles of similar origin are classed as either ice or snow pellets. Hailstorms are generally characterised by strong updrafts, large liquid-water content, large cloud-drop sizes, and large vertical extents. Such conditions enable hailstones to grow from the stage of hail embryo to a hailstone of considerable size by collecting super-cooled water drops. The destructive effects of hailstorms upon plant and animal life, buildings and property and aircraft in flight render them a prime object of weather modification studies. Hail is a rare event with a small horizontal extent, which makes prediction difficult. Its occurrence cannot be entirely captured by current ground synoptic stations. To study hail climatology from direct measurements, data from local hail-pad networks are used (Fraile *et al.*, 2003; Berthet *et al.*, 2011; Eccel *et al.*, 2012). Remote sensing data from radars and satellites can be used as an indirect mean for hail detection (Feral *et al.*, 2003; San Ambrosio *et al.*, 2007; Cecil and Blankenship, 2012).

Berthet *et al.* (2011), for example, evaluated large data sets from hail-pad networks in France. The time variations in hail occurrence during 1989–2009 were computed from the data at 457 stations, which remained unchanged during this period. The authors show that the annual hail frequency was subject to cyclic variations, while the yearly mean intensity was affected by irregular severe hail events. The frequency did not change significantly during the period, while the intensity increased by 70 % – events in April and May were responsible for the mean hail increase observed. A computation of the year-to-year correlation between hail intensity and mean minimum surface temperature for each month suggested that the large hail increase in April and May was at least partially due to the observed concomitant increase in temperature and may therefore be a consequence of global warning. Hail climatology was studied by Eccel *et al.* (2012) with the data from a 271-hail-pad network operated in the Italian Alps since 1974. Many hail indices were investigated in a 35-year period, searching for climatic trends. The results show that, despite a slight, non-significant trend of decrease in the number of events and in the hit surfaces, most energetic indices, which are directly correlated to the damage to crops, have increased in the period, some at considerable rates.

Data combined from several sources are an alternative for studying hail climatology. Kunz *et al.* (2009) analysed different datasets in Baden-Württemberg in southwest Germany for the period 1974–2003. The data comprise thunderstorm days detected at synoptic stations, hail damage data from a building insurance company, large-scale circulation and weather patterns, and convective indices derived from radio-sounding observations. While the mean annual number of thunderstorm days remained almost unchanged, hail damage and hail days increased significantly in the last three decades. Most of the commonly used convective indices that depend on surface temperature and moisture showed a positive trend in both the annual extreme values and the number of days above or below specific thresholds. A relationship was established between the indices and the annual number of hail damage days, yielding correlation coefficients between 0.65 and 0.80. In contrast to this, indices derived from temperature and moisture at higher levels exhibit either a negative or no significant trend. It was shown that the trend directions of the indices could be attributed to differential temperature and moisture stratification in various atmospheric layers. The significant positive trends of both surface temperature and water vapour can be concisely expressed by an increase in potential wet-bulb temperature. This indicates the presence of warmer parcels throughout the whole troposphere during convection.

Surface-based climatologies of hailstorms are limited by inconsistencies in observational networks and reporting practices that vary from country to country. That is why the relevance of hail detection by remote sensing is growing. Radar data combined with sounding information are used to identify hail development. A study published by San Ambrosio *et al.* (2007) identified several radar- and sounding-based indices as more accurate for the Spanish region. Hail detection using S- and C-band radars was reported by Feral *et al.* (2003). A dual-wavelength algorithm was tested with the hail impacts observed with ground-based hail-pad networks and confirmed the ability to detect the hail-bearing cells in real time and location. The use of radar data can be considered as useful, in particular, polarimetric radars are a prospective tool for hail identification. A hail climatology, based on radar data, can be expected in the near future.

Studies dealing with global hail climatology use passive microwave satellite data. Cecil and Blankenship (2012) estimated an 8-year global climatology of storms producing large hail from satellite measurements using the Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E). This allowed a unique comparison between regions that cannot be consistently compared using ground-based records. The AMSR-E measurements are limited to early afternoon and late night. Tropical Rainfall Measuring Mission (TRMM) measurements were used to investigate diurnal variability in the tropics and subtropics. The study shows that European hailstorm activity generally peaks in summer but storm counts are greater in autumn for the Mediterranean. This probably has to do with the Mediterranean Sea remaining warm while cooler air advances from Europe.

3.6 Conclusions on extreme weather phenomena

In this chapter we have considered the evidence of recent changes in extreme weather and presented an assessment of the projections of their future patterns provided by climate models.

There is now an impressive body of data on weather extremes from observations made over recent decades, and the analysis of this has begun to show significant trends in some of the key extreme weather phenomena. In particular, it is clear that there has been a general increase in extreme heat, with a corresponding reduction in cold extremes. Heavy precipitation has also increased in intensity. In the case of wind storms, the evidence is more equivocal: analysis of the last three or four decades suggests that wind storms have increased, but this trend is not seen in the assessments of longer periods. The data quality of the record for extreme convective events, such as thunderstorms, is considered inadequate at present for an assessment of recent trends. However, efforts are underway to remedy this situation with an improved density of observation networks and harmonised data standards.

There have been numerous experiments with models of the climate system on global and regional levels to assess how these current trends may work out in future. These suggest that current trends will continue, with a general increase in heat waves and heavy precipitation. Assessments based on the trends in the underlying causes suggest that wind storms and convective events are both likely to increase in future.

Both observations and experiments with models show considerable regional variation across Europe, with generally heightened effects in the Eastern Mediterranean region.

It seems prudent to invest in high-quality observations and analysis of data and in the development of regional models for studying the impacts of future climates on extreme weather, given the destructive capacity of extreme weather events. For example, it is estimated that wind storms will cause between 30 % and 100 % more damage at the end of this century, unless further adaptive action is taken.

CHAPTER 4 IMPACTS OF EXTREME WEATHER IN EUROPE, ECONOMIC AND INSURED LOSSES, IMPACTS BY SECTOR AND IMPACTS BY REGION

The previous chapter described the major extreme weather phenomena. This chapter describes the impacts these phenomena have on society and the economy. These impacts have the form of disasters for society, sometimes leading to significant loss of life and substantial economic burdens on communities. In some cases, they may have devastating effects on entire countries or regions.

In particular, we consider evidence for trends in the scale of impacts of extreme weather events and the frequency with which they give rise to large-scale disasters. We assess what future climate change may produce in terms of damage and economic loss.

4.1 Changes in the pattern of flooding due to climate change

In summary:

- Projections indicate that flood risk will increase over much of Europe, consistent with increases in the frequency and intensity of heavy rainfall predicted by climate models, which should contribute to increases in precipitation-generated flooding.
- The number of large floods in Europe has increased, but no ubiquitous increasing trend has been detected in observation records of annual maximum floods in Europe.
- Damage from floods has increased, but evidence linking this to climate changes is weak, partly because of a lack of data and partly because of the effect of past flood-risk management. It seems that there has been a measure of adaptation but that exposure of assets at risk has increased.
- The future magnitude and frequencies of floods are very unclear, partly because information about the future evolution of the underlying causes is uncertain but also because of other confounding factors, including the effects of human intervention.

Introduction

Flooding is a complex phenomenon and several causal mechanisms may be involved, including intense or long-lasting precipitation. Lengthy periods of rain are the most common causes of river (fluvial) floods, but colder regions of Europe may also be subject to snow-melt, sometimes enhanced by rain. Floods can also be induced by a collapse of an ice-jam, landslide or outburst from glacial lakes and, occasionally, a failure of a dam or a dike. Inundation from storm surges is discussed in Section 4.2.

Climate-change impacts on river flows depend primarily on how the volume, timing, and phase of precipitation, whether snow or rain, is affected. A robust finding is that warming would lead to changes in the seasonality of river flows, where much winter precipitation currently falls as snow. Spring flows decrease because of the reduced or earlier snowmelt, and winter flows increase, with consequences for flood risk. In regions with little or no snowfall, changes in run-off are much more dependent on changes in rainfall than on changes in temperature, and studies often project an increase in the seasonality of flows, with higher ones in the peak flow season (Meehl *et al.*, 2007b). Climate-driven changes in flood frequency are projected to be complex, depending on the generating mechanism, increasing flood magnitudes, for example, where floods result from heavy rainfall and decreasing ones where floods are generated by spring snow-melt.

There are other causes of destructive abundance of water. Intense rain, for example, from an extreme convective event such as summer storm may lead to an urban flash flood. A groundwater flood, which may last for months, occurs when the water table in an aquifer, such as limestone, comes to the ground surface at lower places.

Current flood risk

A universal increase in flood maxima is not evident in Europe. Individual river gauges in Europe provide no conclusive and general proof as to how climate change has affected flood risk so far. There is evidence, however, that the number of large floods has increased (Figure 4.1).

The key causal factor, however, has shown an increase. Globally, over the past 50 years, heavy precipitation events have been on the rise for most extra-tropical regions, corresponding to a warmer Earth surface and lower troposphere. This includes widespread increases in the contribution to total annual precipitation from very wet days, days on which precipitation amounts exceed the 95th percentile value, in many land regions.

A similar trend is seen in Europe; according to observations, heavy precipitation has been on the rise in a warming climate over much of the region. However, intense precipitation in Europe exhibits complex variability and a lack of a robust spatial pattern. The principal seasonal effect is the increase in extreme precipitation in winter with heavy precipitation events becoming more frequent, even in regions with decreasing total precipitation amounts.

There is an increasing body of evidence showing unequivocal warming of the atmosphere, at all spatial scales. Corresponding precipitation changes have been less regular, but increases over land north of 30° N over the period 1901–2005 and decreases over land between 10° S and 30° N after the 1970s have been observed.

The rainfall statistics in Europe are strongly influenced by inter-annual and inter-decadal variability. Seasonality and structure of precipitation is subject to change as global warming affects the hydrological cycle. Winter precipitation has increased over much of Europe, in particular in the north, while summer precipitation has decreased, particularly in the south. Short and temporally isolated rain events have been regrouped into prolonged wet spells.

However, there are problems with availability of precipitation data, in general, and also with data homogeneity and accuracy, in particular in less developed countries, worldwide. These problems with data are particularly severe for heavy precipitation.

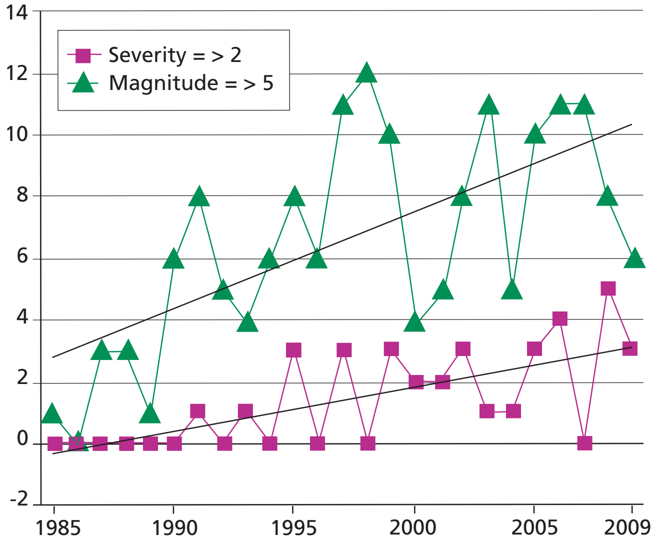


Figure 4.1 Large floods in Europe (with severity 2 and magnitude ≥ 5)
For an explanation of severity and magnitude see Box 4.1 (Choryński *et al.*, 2012).
Source: Kundzewicz *et al.*, 2013.

Despite the ambivalence of the precipitation data, flood damage has strongly increased due to a wide range of factors, and floods are an increasingly acute problem. Flood risk and vulnerability have had a tendency to increase over many areas in Europe, due to a range of climatic and non-climatic impacts whose relative importance is site-specific. Material damage caused by floods has been rising and the death toll continues to be high. Even if the most destructive floods occur elsewhere, Europe is not immune, as illustrated in Table 4.1.

Table 4.1 Floods in Europe with the highest material damage (inflation-adjusted)
Source: after Choryński *et al.*, 2012.

No.	Date	Country	Damage US$ million inflation adjusted	Fatalities
1	August 2002	Germany, Czech Republic, Austria	20 933	47–54
2	November 1994	Italy	5 944–13 820	64–83
3	November 1966	Italy	13 594	70–116
4	October 2000	Italy, France, Switzerland	10 231	13–37
5	August 1983	Spain	2 764–8 623	40–45
6	July 1997	Poland, Czech Republic, Germany	2 744–8 095	100–115

Changes in flood risk have been caused by socio-economic, terrestrial, and climatic factors. Deforestation, urbanisation, and reduction of wetlands diminish the available water storage capacity and increase the runoff coefficient, leading to growth in the flow amplitude and reduction in the time-to-peak of a flood triggered by typical intense precipitation such as design precipitation, the amount of precipitation that is assumed in design of buildings and engineering structures. However, almost ubiquitously, what used to be typical intense precipitation in the past is very likely to become more intense in a future, warmer climate (Coumou and Rahmstorf, 2012). Furthermore, there are numerous socio-economic factors that influence flood risk, including exposure, vulnerability, adaptive capacity, risk awareness and damage potential, which is driven by the size of the population and its wealth, the state of economic development in flood-prone areas and risk perception (Kundzewicz, 2012; Kundzewicz *et al.*, 2013). Societies have become more exposed as human encroachment into unsafe areas has increased (maladaptation). Flood risk has been greatly intensified by humans, who – to use the language of mechanics – have increased the load and decreased the resistance of the system; both the flood magnitude and the flood damage have been on the rise.

However, no conclusive climate-change signal has been found in analysis of time-series of high river flows observed so far, worldwide (Kundzewicz *et al.*, 2005). According to Wilby *et al.* (2008), detection of climate signals is inherently difficult, even at global or regional scales, because of the low signal-to-noise ratio. A relatively weak climate change signal, if any, is superimposed on a strong natural variability of rainfall and river discharge, further confounded by land-use change. Hence, Wilby *et al.* (2008) speculate that statistically significant trends are unlikely to be found for decades.

According to the SREX report (IPCC, 2012), there is yet no widespread evidence of climate-driven observed changes in the magnitude or frequency of floods at a global scale, mainly due to lack of reliable data and confounding effects from changes in land-use and water management. Nevertheless, there may be some indications that anthropogenic climate change could be responsible for increased risk of rainfall-dominated floods in some watersheds in the British Isles. Calculations based on RCMs and GCMs in conjunction with hydrological models suggest that increased frequency and/or magnitude may be expected for floods, although such model results are sensitive to a range of subjective choices and are therefore regarded as inaccurate.

When examining comprehensive river discharge data for Europe, Kundzewicz *et al.* (2005) found that the overall maxima for 1961–2000, the period subject to study, occurred more frequently, 46 times, in the later sub-period, 1981–2000, than in the earlier sub-period, 1961–1980, 24 times. However, the results of a global change detection study of annual maximum river flows (Kundzewicz *et al.*, 2005) do not support the hypothesis of an ubiquitous increase in annual maximum river flows. It is important to keep in mind, however, that society has adapted rivers and flood defences for centuries and that a comparison between subsequent periods may not provide a clear-cut description of the changing climate.

Kundzewicz *et al.* (2013) examined changes in flood occurrence in Europe over the past 25 years, based on data from the European Floods Observatory – Figure 4.1 shows changes in numbers of large floods with high severity index and magnitude (Box 4.1).

Flood risk in future

At present there is considerable uncertainty about how the underlying factors affecting flooding will respond to climate change. Due to the high number of unknowns associated with projections of precipitation, the direction of future change in annual runoff varies between different climate models, even when the same greenhouse-gas emissions scenario is used.

However, Hirabayashi *et al.* (2008) and Dankers and Feyen (2008) have developed projections of flood hazard in Europe based on climatic and hydrological models. They produced grid-based maps of changes of recurrence over a 100-year period, comparing the control period with projections for the future. According to Hirabayashi *et al.* (2008), floods corresponding to a return period of 100 years are expected to become considerably more frequent in much of Austria, France, Germany, Italy Poland and Switzerland (Figure 4.2). In contrast, over much of Russia and Scandinavia, floods corresponding to 100-year return interval for the current baseline may get less frequent. In aggregate terms, events with similar magnitude to the studied floods are projected to become more frequent for 40 % of the area of Europe, and for 30 % of the area of Europe, the mean recurrence intervals are projected

BOX 4.1 FLOOD SEVERITY AND MAGNITUDE

Severity is a discrete index and not an exact descriptive statistic. It uses expert judgements to translate news reports such as 'largest flood in 50 years', or 'as large as the flood of 2002' into approximate numerical estimates of how unusual the flood was. Three flood severity classes were defined as follows:

- Severity class 1 includes large flood events, often causing significant human and economic damage, with an estimated, commonly from news reports, mean return period – recurrence interval – of the order of 10–20 years.
- Severity class 1.5 contains very large events whose return period is greater than 20 years but less than 100 years.
- Finally, severity class 2 includes truly extreme events with an estimated return period equal to or greater than 100 years.

The mean return period is the average interval between two events with magnitudes equal to or greater than the level concerned. It is estimated from reports of significant floods, for example in newspapers.

Flood magnitude is defined as a function that takes account of severity as defined above, the duration of the flood and the flooded area. The index is the product of duration in days, severity as given above and the area affected in square kilometres. It is given on a logarithmic scale, similar to the Richter scale for earthquakes. Flood magnitudes of 7, 8 or 9 represent very large magnitude events.

For details of these indices, see Choryński *et al.*, 2012.

to decrease to less than 50 years in 2071–2100 – effectively the frequency will at least double.

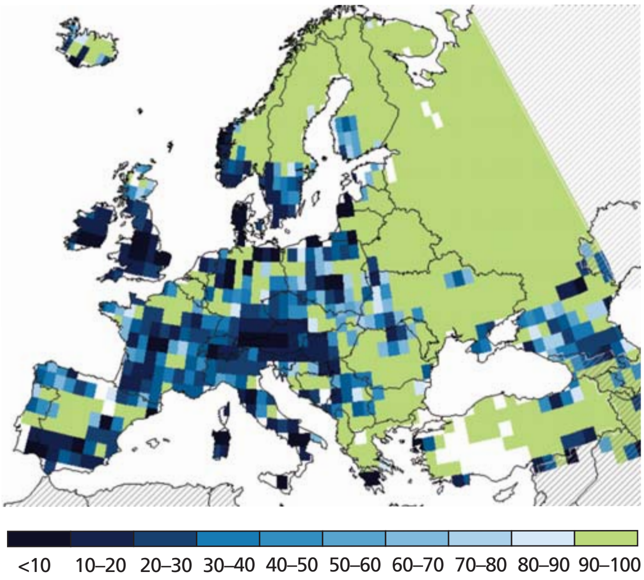
Studies devoted to the impact of climate change on future flood damage are scarce (Kundzewicz *et al.*, 2010). Feyen *et al.* (2008) arrived at expected annual damage at the EU and country level. They assumed that the flood protection level depends on the country's GDP based on protection up to 100-year, 75-year, and 50-year flood for countries with GDP above 110 %, 55–110 % and >55 % of the average EU 27 GDP, respectively.

However, they made the simplifying assumptions that there would be no further adaptation to increasing flood levels and no growth in the value of stock at risk. Under these assumptions, the annual damage, it is € 6.5 billion at present, was projected to nearly treble to € 18 billion in 2071–2100 under the SRES A2 scenario. There are five countries in each of which the expected annual damage in the future was projected by Feyen *et al.* (2008) to exceed € 1 billion. Among 25 countries of the EU, where non-zero flood damage in the control period occurred, up to 80 % increases are projected in 20 and decreases of up to 85 % are projected in five.

The European Joint Research Centre (JRC) has established a floods portal[9] (accessed May 2013) based on results from Dankers and Feyen (2009) and an ensemble consisting of simulations from two RCMs. Both RCMs have been run with boundary conditions from two GCMs and two scenarios of greenhouse gas emissions. An

Figure 4.2 Recurrence interval (return period) of today's (1961–1990) 100-year flood at the end of the 21st century (2071–2100), in case of scenario SRES A1B

Source: Map from Kundzewicz *et al.*, 2010 prepared using results from Hirabayashi *et al.*, 2008.



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[9] http://floods.jrc.ec.europa.eu/home.html (accessed May 2013)

important conclusion from Dankers and Feyen (2009), however, was '*at the scale of individual river basins, using a different combination of climate models or assuming a different emissions scenario sometimes results in a very different or even opposite climate change signal in flood hazard. We therefore believe that a multimodel approach as adopted in the present paper (Dankers and Feyen, 2009) provides the best way to address the various uncertainties in impact studies of hydrometeorological extremes*'. Although the floods portal presents results from a multi-model, multiple-realisation and multi-scenario approach, it is clear that the ensemble, on which the results were based, is too small to represent the range of possible outcomes (Deser *et al.*, 2012).

Mudelsee *et al.* (2003) argued that recent anthropogenic changes in atmospheric composition are expected to cause climate changes and perturb the hydrological cycle and as a consequence to increase flood risk. However, they reported that the past decades' observations from Europe do not show a clear increase in the flood occurrence rate and, during the past 80–150 years, there has been a decrease in winter flood occurrence in both the Elbe and Oder rivers. The reduction in winter flood occurrence was attributed to fewer events of strong freezing and less frequent breaking of river ice at the end of the winter, which may function as a water barrier and cause floods. The summer floods showed no trend, consistent with trends in extreme precipitation occurrence.

Pall *et al.* (2011) considered a specific event, the floods in the United Kingdom in Oct/Nov 2000, with a very large ensemble of runs starting from roughly the same initial conditions to see how often the flooding event would occurred by tracking run-off and stream-flow as part of their modelled set-up. Their analysis indicated that in nine out of ten cases, the chance increased by more than 20 %, and in two out of three cases by more than 90 %. In their analysis, flooding was defined as more than just intense rainfall. Min *et al.* (2011) also analysed extreme precipitation on a global scale, for which they compared observed and multi-model simulated past changes. Their conclusion was that anthropogenic greenhouse-gas emissions are at least partly responsible for more intensive heavy precipitation.

Moreover, hydrological studies such as those by Kundzewicz (2012) and Mudelsee *et al.* (2003) find no statistically significant trends in the flood statistics, whereas more climate-model-based studies such as those of Pall *et al.* (2011) and Min *et al.* (2011) indicate that some of the conditions important for flooding have changed over the past ~50 years.

The SREX report (IPCC, 2012) says that some studies have found no climate-change contribution to European economic loss trends from floods since the 1970 and some analyses have identified increased damage to forests in Sweden and Switzerland, the connection between these two were not elaborated further in the SREX report. However, the increases in forest disturbance may have been due to changes in forest management. In Chapter 4 of the SREX report, it is also stated that droughts can damage trees. For instance, damage was observed in the stone pine, *Pinus pinea*, and the European beech, *Fagus sylvatica*, from central Italy after the 1989 drought. Furthermore, precipitation deficit and hot conditions have caused defoliation and mortality in the Scots pine, *Pinus sylvestris*, in the largest inner-alpine valley of Switzerland (Valais) during 1996–2002. The SREX report also observes that adaption to projected changes in the wind, for example through sea defences, may have additional indirect beneficial effects on estimated losses.

Flooding is the most frequent natural disaster in Europe and there has been an increasing trend in associated economic losses over recent decades which to a large extent may be attributed to an increasing exposure of wealth. An increase in the frequency of heavy precipitation will result in more flash floods that also represent one of the most common weather-related causes of fatality. Floods also destroy infrastructure such as roads and railways, and increased runoff volumes may pose a risk of dam failure. Glacial lake outbursts in mountain regions also have potentially devastating impacts on society.

4.2 Storm surges: extreme sea level due to storm surge and climate change

Temporary increases in sea level, above the level of the tide, known as storm surges, are a major geophysical risk in low-lying coastal areas. They last for a period ranging from few minutes to a few days and are caused by low atmospheric pressure within deep low-pressure systems combined with the force exerted on the sea by associated strong winds. The sea level may be further increased by the geometry of the coast, which can have a funnelling effect. Surges are more damaging when they occur at high tide. Coastal protection measures are very important to reduce the risk that surges pose to vulnerable coastal areas.

In Europe, areas of particularly high storm-surge risk are the North Sea coast, some areas of the Baltic coastal zone, parts of the Iberian west coast and few areas of the Mediterranean, especially in the Gulf of Lyon and in the northern shores of the Adriatic. The height of extreme surges tends to be lower in Southern Europe than in Northwest Europe, especially in the North Sea, which in some areas of its southern coast reaches values above 2 m for a 50-year return period event (Lowe and Gregory, 2005). Storm surges were responsible for major disasters in 1953 in the Netherlands and the United Kingdom.

Climate change influences the extreme water levels associated with storm surges through two different mechanisms: average sea-level rise and changes in the number, path and strength of cyclonic storms. Global mean sea level rose by an average of 17 cm over the 20th century (Church and White, 2006) driven largely by the thermal expansion of the upper ocean layers and the melting of glaciers, ice caps and ice sheets, associated with anthropogenic climate change. The higher sea level resulting from global warming does not directly impact the amplitude of the storm surges, however, the sea level rise is expected to magnify the total effect as the sum of both raised levels and wind-driven surges. Since the 1980s the mean sea level has risen at an average rate of 3.4 mm per year (Cazenave and Llovel, 2010). Estimates of future sea-level rise vary: the IPCC AR4 gives 180–590 mm in the period 2090–2099 relative to 1980–1999, and a number of recent studies project a rise at the end of the century exceeding 1 m if greenhouse-gas emissions continue to escalate (Rahmstorf, 2007; Vermeer and Rahmstorf, 2009). There are significant regional differences in sea-level rise due to changes in ocean circulation and atmospheric pressure. Furthermore local mean sea level, the sea level with respect to a local land benchmark, is influenced by vertical land movements which can have annual rates of the same order as sea level changes induced by climate change. Long-term average local sea-level rise on European coasts changed, depending on the region, at a rate of between -0.3 mm/year in Dublin and 2.8 mm/year in Heimsjö, Norway during the 20th century (EEA, 2007). While the global sea-level rise projected for the 21st century threatens many vulnerable low-lying coastal areas, it is the extremes of sea level associated with storm surges that are very likely to cause significant damage (Lowe and Gregory, 2005). Climate-change impacts in coastal cities are a major global challenge this century with millions of people and assets valued at many trillions of US dollars exposed (Hanson *et al.*, 2011).

BOX 4.2 COPENHAGEN FLASH FLOOD

The flash flood in Copenhagen on 3 July 2011 resulted from an extreme downpour that lasted for two hours. Total rainfall recorded was 135 mm at the Copenhagen Botanical Garden. The Danish Meteorological Institute reported that this amount was close to a 100-year event, and about twice the normal July rainfall in northern Sjælland. The event caused severe flooding in central Copenhagen.

In Europe some recent studies project an increase in the number and intensity of storms over Northwestern Europe, in particular the United Kingdom and Scandinavia (Beniston *et al.*, 2007). There is evidence that the extreme wave height will increase with the higher storminess (Caires *et al.*, 2006). For the North Sea a 100-year surge event could become 10–20 cm higher than today by the 2080s (Woth *et al.*, 2006). The projected increases in storm surge in 2071–2100 depend on the RCM used, according to Beniston *et al.* (2007) who analysed the PRUDENCE results. The HIRHAM-H model suggested 50 cm along the Dutch, German and Danish coasts, whereas the RCAO-H model gave 25 cm. Marcos *et al.* (2011) find that in the Mediterranean region the storm-surge frequency and magnitude tend to decrease during the 21st century, due to a tendency for lower storminess.

Storm-surge projections under climate change scenarios are affected by considerable uncertainties related to the difficulty in modelling storm events and wave climate at the regional and local levels, the limited amount of data available and changing bathymetry due to sedimentation and erosion. Published research points to relatively small to moderate changes in the extreme heights of storm surges in Europe caused by global warming. The projected wind-related surge increase at the end of the century is particularly significant in the southern North Sea with maximum values of 20–25 cm relative to the control period of 1960–1990 (Storch and Woth, 2008). Increases in the number of storm-surge events and the height of extreme surges are also projected for the Irish coastal areas except on the south coast (Wang *et al.*, 2008).

In the absence of protection, future extremes of sea level associated with storm surges coupled with global sea-level rise will significantly increase flood risks in Europe. Although there is considerable uncertainty in future sea-level rise it is important to start implementing long-term adaptation in the coastal cities located in the most vulnerable areas. Planning and new coastal infrastructure investments should take into account the risk over the entire lifetime of the infrastructures and allow for flexibility, making it possible to upgrade them if sea-level rise turns out to be larger than expected. Furthermore it is necessary to improve flood emergency plans, early-warning systems and evacuation schemes.

Reckermann *et al.* (2011) noted that the southern coasts of the Baltic Sea are especially vulnerable to storm surges, due to the low-lying lagoon-type coastlines. The effects of storm surges may be more severe than expected from wind events alone, because, in contrast to the northern parts of the Baltic Sea, there is no land uplift counteracting global sea-level rise.

Simpson *et al.* (2012) considered the effect of different physical factors on local sea level. These included spatial variations in ocean density, circulation, ice- and ocean-mass changes, vertical land motion arising from past surface-loading change, as well as gravitational effects associated with changes in ice, ocean and terrestrial mass. They estimated the upper bound of the 21st century sea-level changes in Norway to be 70–130 cm, however, due to many unknowns, they could not provide likelihood estimates for this interval. Simulations of wave climate and future storm surges in the North Sea and the Norwegian Sea suggest a dependency on the choice of global climate model (Debernard *et al.*, 2002; Debernard and Sætra, 2002). The greatest projected change in wave heights were seen at high latitudes, the Barents Sea, and the North Sea, reflecting projected changes in winds. The analysis by Debernard *et al.* (2002) and Debernard and Sætra (2002) indicated future decreases in wave heights and wind speeds over the Norwegian Sea.

4.3 Droughts and food security

In summary:

- In Europe, droughts and prolonged dry spells are relatively rare events, which exhibit a large natural variability in frequency and intensity. Consequently, it can be expected that a relatively long time would be required to acquire a sufficient record to detect trends.
- However, currently available records suggest that, while increasing summer dryness has been observed in Central and Southern Europe since the 1950s, no consistent trends can be seen over the rest of Europe.
- For the future, summer dryness is expected to increase in Central and Southern Europe during the 21st century, leading to enhanced risk of drought, longer dry spells and stronger soil moisture deficits.

Introduction

Although the impacts of droughts do not come through sudden events, such as floods and storms, drought is one of the most damaging types of natural disaster over long periods, with severe potential impacts on agriculture, food production and the water supply. Examples of prolonged European droughts include the 2005–2006 drought over the Iberian peninsula, the dry conditions associated with the 2003 heat wave, and the 1975–1976 drought over the southern British Isles and northern France. The time scales vary from short dry spells of several weeks without any rain to longer periods, up to months. Globally, droughts can be of considerable length, for example, the length of the Dust Bowl in the 1930s over the USA or the Big Dry in Australia at the start of the 21st century with basically a whole decade of sustained anomalously low rainfall.

There is no universal definition of drought, and the various definitions suggested in the literature depend mainly on the objective of their use. Generally, drought is a temporary dry period and is often classified into the following three types:

- meteorological drought: defined as prolonged abnormal deficit of precipitation;
- agricultural drought: also soil-moisture drought – a precipitation shortage during the growing season that affects agriculture or ecosystem functions;
- hydrological drought: below-normal stream-flow in rivers and lake and groundwater levels.

A lack of precipitation, a meteorological drought, often triggers agricultural and hydrological droughts, but other factors, including more intense but less frequent precipitation, poor water management or erosion, can also cause or enhance these droughts (Dai, 2011a). Integrated approaches define droughts not only as a lack of rain but more generally as an excess of demand –potential evapotranspiration, the combination of evaporation from land and transpiration from plants, and runoff – over supply – precipitation – which is a first

Frank Barratt/Getty Images

Figure 4.3 Drought advisory in the United Kingdom in 1975–1976
An unprecedented 16-month period with strong precipitation deficits started in May 1975. Averaged over the 16-month period, precipitation was less than 50 % of the long-term mean at many stations in southern England and northern Brittany.
Source: Morris and Ratcliffe, 1976.

order approximation for the drying of the land surface (Gregory *et al.*, 1997). There is a wide variety of different drought indices, which, depending on their use, differ in combining information on precipitation, evapotranspiration, runoff, temperature and soil moisture.

Droughts in northern mid-latitudes are in general associated with strong and persistent anti-cyclonic circulation anomalies and a poleward displacement of the jet stream (Namias, 1983; Trenberth *et al.*, 1988). Land surface/soil moisture-atmosphere feedbacks and interactions can amplify and prolong dry spells and droughts. The drought response to an atmospheric forcing thus depends, among other factors, on the soil characteristics and rooting depth of the ecosystems.

Observed changes in droughts in recent decades

In summary:

- Globally, dry areas are growing, by a factor of more than two over the past 40 years.
- However, observations show inconsistent trends in dryness over Europe in recent decades.
- The most consistent signal for increase in dryness in Europe has been observed in Central and Southern Europe since the 1950s. No signal or inconsistent trends have been observed in other regions.

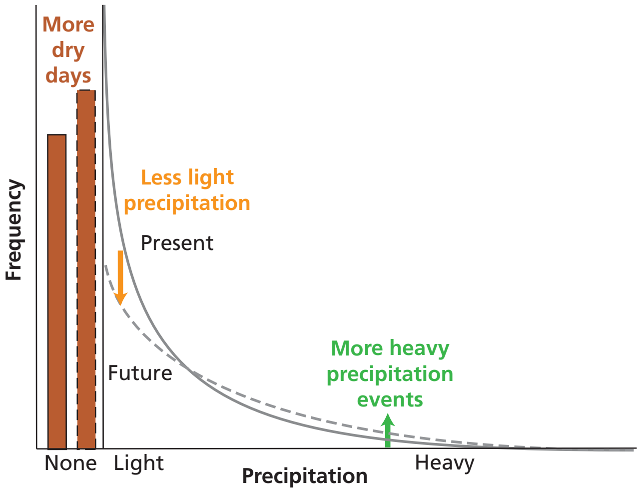


Figure 4.4. Potential changes in frequency and intensity of precipitation extremes in a changing climate
Current and potential future distributions are depicted with full and dashed lines, respectively.
Source: after CH2011, 2011.

Dai *et al.* (2004) showed that globally, very dry areas more than doubled, from 12 % to 30 % of the land area since the 1970s. However, over Europe the trends are less clear. The most consistent signal for an increase in dryness in Europe has been observed in Central and Southern Europe since the 1950s. No signal or inconsistent trends have been observed in other regions including Northern Europe (Kiktev *et al.*, 2003; Alexander *et al.*, 2006; van der Schrier *et al.*, 2006; Sheffield and Wood, 2008; Dai, 2011a).

BOX 4.3 CLIM-RUN

A set of case studies, known as CLIM-RUN, has provided a real-world context where experts and end-users are brought together on questions concerning the Mediterranean region, recognised as a climate-change hot-spot (ICCS2, 2012). A discussion concerning climate services in agriculture and food security during the second International Conference on Climate Services (ICCS2) in Brussels in September 2012 concluded that historic observations warrant investment as a free public good, and that many promising opportunities to improve security and livelihoods of vulnerable rural communities depend on historic observations and can be hindered by gaps in availability and access.

As noted, droughts are rare and it takes a considerable time to accumulate a record of sufficient instances for statistical analysis. Sheffield *et al.* (2012), however, suggested that an approach based on a physical understanding of the complex relationships between climate and hydrological variability could be used for assessing the magnitude of impacts of global warming. They argued that previously reported increases in global drought had been overestimated and that Palmer Drought Severity Index (PDSI) assessments had been based on over-simplified models of potential evaporation.

A study for the Middle East (Black *et al.*, 2010) reported decreasing winter rainfall over Southern Europe and the Middle East and increased rainfall further north, caused by a poleward shift of the North Atlantic storm track and a weakening of the Mediterranean storm track. Nastos and Zerefos (2007) have shown that in Athens, Greece, daily precipitation parameters for the last two decades do show a significant difference both in the shape and scale of their distributions when compared to any previous period from the 1890s through to the 1970s. The changes in heavy and extreme precipitation events in this part of Southeastern Europe have had significant environmental consequences with considerable damage and loss of life. In this part of Europe, Kioutsioukis *et al.* (2010) have shown that there is a shift towards a drier climate, while extreme rainfall events increased in variability without following any coherent regional pattern. Changes in the precipitation extremes are associated with changes in both the scale and location of the fitted distribution. The highest range of change was found for the scale parameters for both temperature and precipitation extremes, suggesting that the most influential factor is the inter-annual variability of the extremes.

BOX 4.4 MEDITERRANEAN WATER DEFICIT

A water deficit in the Mediterranean region that averages about 2.4 mm/day was identified by Romanou *et al.* (2010), and there is a significant east–west asymmetry ranging from 3.5 mm/day in the eastern part to about 1.1 mm/day in the western part of the basin. The zonal asymmetry in the water deficit is driven by evaporation differences, which in turn are determined by variability in the air–sea humidity difference in the different parts of the Mediterranean basin. The Black Sea freshwater deficit is 0.5 mm/day, with maxima off the northern coast of 0.9 mm/day, attributed to both evaporation maxima and precipitation minima there. The trend analysis of the freshwater budget shows that the freshwater deficit increased in the 1988–2005 period. The prominent increase in the eastern part of the basin is present in the satellite and several reanalysis datasets. These findings were based on satellite retrievals of surface evaporation and precipitation from the Hamburg Ocean Atmosphere Parameters and Fluxes from Satellite Data (HOAPS-3).

Water deficit is due to increases in evaporation, while precipitation does not show any consistent trends in the period. Similarly, in the Black Sea, trends in the freshwater deficit are mainly due to evaporation, although year-to-year variability is due to the precipitation patterns.

According to the SREX report (IPCC, 2012), there have been no statistically significant changes in observed drought conditions in Europe, except for one analysis of the Mediterranean region. Some studies suggest there has been a contrasting dryness trend, with a movement towards drier conditions in southern and eastern parts of Europe and less dryness elsewhere. Other indicators of drought were tendencies towards increased numbers of consecutive dry days in the southern and central parts of Europe and increasing salinity in the Mediterranean. Salinity reflects the balance between evaporation, river discharge and precipitation. The SREX report concludes that there is medium confidence that anthropogenic influence has contributed to some changes in drought patterns since the 1950s and in particular trends towards more intense and longer droughts in Southern Europe.

Projected future changes in droughts

Projections based on knowledge of physical process

Increasing atmospheric greenhouse-gas concentrations are expected to lead to more evaporation (Trenberth, 2011), earlier snowmelt and vegetation onset, the three factors contributing to enhanced summer drying. Thus, a long-standing result from global coupled models has been a projected increase in summer drying in the mid-latitudes in a future warmer climate, with an associated increased likelihood of drought. Regionally, this response can be substantially modified by potential atmospheric circulation changes.

Plausible future scenarios based on climate model simulations
Based on the balance of evidence coming from multi-model experiments, the following changes in summer dryness are expected in the course of the 21st century:

- Mediterranean, Southern and Central Europe: summer dryness is expected to increase during the 21st century – longer dry spells, stronger soil moisture deficits;
- Northern Europe: no major changes in dryness are expected until the end of this century.

Schär *et al.* (2004) and Coumou and Rahmstorf (2012) proposed that heat waves and droughts are connected, where there is an amplifying effect of soil moisture.

Droughts, agriculture and food security
The 2003 and 2010 heat waves and the associated dry conditions resulted in major regional crop shortfalls. The drought conditions, and associated fires in the 2010 heat wave also caused a 25–30 % drop in the forecast of Russia's annual grain crop production, compared with 2009. Due to the loss of crops and the shortage for domestic markets, a ban on grain export was imposed by Russia, one of the world's largest wheat exporters. However, for an integrated assessment, the impacts of heat waves on agriculture need to be evaluated on a regional scale for each specific crop type. During some events, such as the 2003 heat wave, both positive and negative effects on crop production were reported.

4.4 Examples of extreme weather impacts on specific sectors

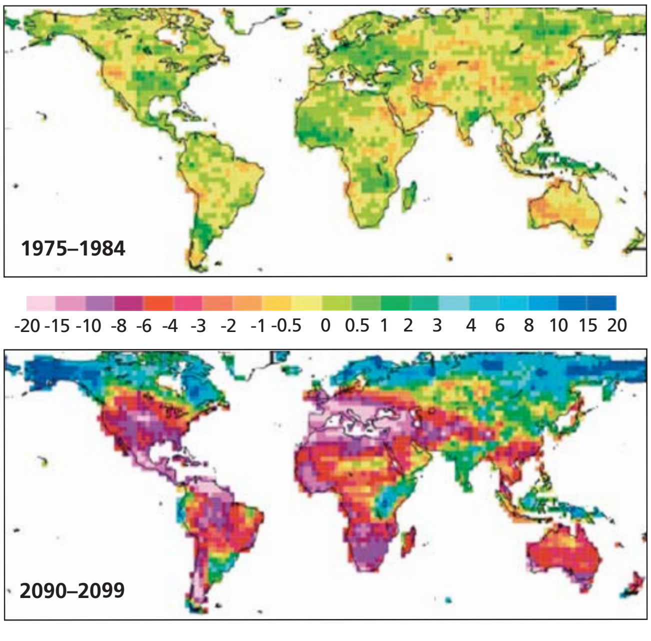
The energy sector

In summary:

- Climate change is expected to affect both demand and supply in the energy sector, with higher demand for cooling during heat waves in summer and less demand for heating in winter. Changes in demand will affect the seasonal pattern of power load in the transmission network.
- Warming can affect the efficiency of power production from thermal power plants, increased precipitation in Northern Europe is expected to enhance hydro-electric power production, changes in mean wind conditions are expected to affect wind-power generation, and cloudiness to affect the output from solar power generation.
- Extreme events may disrupt energy supplies, mainly through damage to the transmission network.

The Nordic-Baltic research project Climate and Energy Systems (CES), involving 31 partners from Northern Europe, aimed to study climate impacts on the Nordic electricity system for the next 20–30 years. The main objective was to enhance the understanding of the natural variability and predictability of climate and renewable energy systems at different scales in space and time. The project also aimed to assess risks from changes in the probabilities and nature of extreme events, develop guiding principles for decisions under climate variability and change and adaptation strategies, and facilitate a structured dialogue with stakeholders. Another research project, CELECT (Cicero, Norway), has also addressed climate-change impacts on the electricity sector and, for Norway, the increased precipitation projected is expected to be favourable for hydro-electric power production. The value of more precipitation will, however, depend on the effect of a changing climate on both the demand and the loading of the network. Linnerud *et al.* (2011) observed that a warmer climate

Figure 4.5 Mean annual values for a self-calibrated Palmer Drought Severity Index for 1975–1984 (top) and 2090–2099 (bottom)
Calculated using the 22-model IPCC AR4 models and SRES A1B 21st century simulations. Red to pink areas are extremely dry (severe drought) while blue colours indicate wet areas relative to the 1950–1979 mean.
Source: Dai, 2011a.



might result in lower thermal efficiency and reduced load in thermal nuclear power plants. The number of shutdowns could also become more frequent due to cooling-water restrictions. They used different European datasets and econometric strategies to identify these two supply-side effects:

- a rise in temperature of 1° C would reduce the supply of nuclear power by about 0.5 % through its effect on thermal efficiency;
- droughts and heat waves could cause production losses in excess of 2.0 % per degree C for power-plant cooling systems, which are constrained by regulations as well as by physical laws and access to cooling water.

Mideksa and Kallbekken (2010) further noted that climate change is likely to impact electricity markets through both electricity demand and supply. Higher temperatures are expected to increase electricity demand for cooling and decrease demand for heating. Extreme weather events, and secondary effects such as wildfires, may impair electricity generation, transmission and demand, and changes to usage of air conditioning will affect the power load of the transmission network. The effect of climate change on the supply of electricity from non-thermal sources is expected to show substantial geographical differences due to regional variations in temperature and precipitation. However, the need for more research remains, to improve understanding of how climate change will influence the electricity market.

Rübbelke *et al.* (2010) concluded '*during the heat waves in 2003 and 2006 nuclear power plants in several European countries had to reduce or shut down production due to reduced access to cooling water, regulation of maximum temperature of the returned cooling water and other limitations in the cooling system. Such nuclear power supply disruptions may have a significant impact on energy supply security in Europe; as nuclear power accounts for 28 % of the total power supply, each nuclear reactor accounts for a considerable amount of power and nuclear reactors are typically located in the same geographical area with access to the same source of cooling water*'.

Changes in the wind climate are expected to have an influence on wind-power and wave-power output, but there are still uncertainties about future changes in wind speed over Northern Europe (Debernard *et al.*, 2002; Debernard and Sætra, 2002; Pryor *et al.*, 2005, 2006; Beniston *et al.*, 2007; Leckebusch *et al.*, 2008; Pinto *et al.*, 2011; Bronnimann *et al.*, 2012) related to the chaotic nature of large-scale atmospheric flow (Deser *et al.*, 2012). Similarly cloudiness, which influences the amount of sunshine that is available for solar power, is affected by the large-scale atmospheric flow in Northern Europe, which is strongly affected by such natural variations as the NAO. For Southern Europe, on the other hand, an intensification of the subsidence associated with a poleward expansion of the Hadley cell (Seidel *et al.*, 2008) and fewer rainy days may favour increased solar power production.

Changes in the wind climate may also affect power infrastructure, including above-ground transmission systems, and change the pattern of pollution from power stations. Wind atlases can be used in planning the location and construction of power stations and nuclear plants, and in establishing plans to respond to emergencies and extreme events (ICCS 2, 2012). However, available atlases are based on current conditions and require revision to take account of changing patterns of extreme events.

Impacts of extreme weather on human health

Chapter 4.4.5 of the IPCC SREX report (IPCC, 2012) focuses on Europe and notes that there are mounting concerns about increasing heat intensity in major European cities, where building characteristics, waste heat from domestic and office equipment, and lack of open green areas make matters worse. The most vulnerable include the elderly, the sick, and the socially isolated.

There has, according to the SREX report, been a rising trend in deaths caused by avalanches due to an increased presence of people in mountainous regions for recreation and tourism. Increased winter precipitation may affect snowpack and length of the snow season, and thus influence avalanche formation.

Epstein and Ferber (2011) outline links between global warming and a wide range of health threats, including cholera, malaria, Lyme disease and asthma. They also suggest that the influence of environmental change on agriculture and unmanaged ecosystems has consequences for human health, through changes in populations of pests and the production of pollen, which can influence diseases, asthma, and allergies. Health issues for which they identify connections to climate and the environment include: malaria (floods, temperature), asthma (heat waves), cholera (floods, temperature), meningitis (droughts), insect-borne disease (heat waves), blue-green algae, hantavirus, respiration illness (heat waves, fire and smoke), dengue fever, encephalitis, and Rift Valley fever. Although some of these health threats are not currently present in Europe, changes in the range of disease vectors, agricultural practice and air travel make them a cause of potential concern for the future.

The expected changes in demography will also have implications for the connection between environment and health, as aging populations in Europe increase the number of people vulnerable to heat waves. An aging population is also more vulnerable to floods, directly as they cause deaths and injuries and indirectly as they are frequently followed by infectious diseases. New settlement patterns have made people and properties more exposed to extreme weather. Heat waves combined with urban heat islands can, according to SREX, result in high mortality rates amongst the elderly, the unwell, the socially isolated and outdoor workers. Heat waves will in particular become a future concern for big cities, where they will have detrimental effects on air quality.

Heat waves in the Mediterranean region may have the greatest health impact in coastal regions with higher relative humidity, but projections cannot be made with any great confidence as the climate models are not able to account for the moderating effect of sea breezes on the heat waves.

Droughts and heat waves can lead to more burns and smoke inhalation from wildfires. Indirect health impacts, however, are often not well documented, although these may include illness or injury from disruption of human infrastructure for basic needs such as medical services, exposure to toxins after flooding, increased susceptibility to infections, stress and mental illness among the environmentally displaced – for example, acute traumatic stress, post-traumatic stress disorder, grief, depression, anxiety disorders, somatoform disorders, drug and alcohol abuse. Hence indirect health effects may represent a large but unaccounted-for cost of extreme weather events.

Extreme events may affect food security according to the SREX report, both through production and through impairing the delivery chain (transport infrastructure). There are some studies indicating that the current warming trends have already affected crop yields, which have declined due to warmer conditions. For Europe, an increase in production in northern regions is expected to be offset by a decrease in the south. Many crops are sensitive to extreme temperatures occurring at or just before the critical time of their pollination phase. Extreme high temperatures during grain-filling of wheat may also alter the grains' protein content, and heat waves during grain-filling may be one of the most significant factors affecting both yield and quality of wheat flour.

The combination of anomalously high temperatures, atmospheric humidity and air pollution has resulted in a dramatic increase in mortality during recent European heat waves. Tens of thousands additional deaths were recorded during the 2003 (Robine *et al.*, 2008) and 2010 heat waves. The mortality associated with the heat waves affected mostly, but not solely, elderly people and persons with pre-existing medical conditions. The mortality increase, however, was far from compensated by a mortality displacement – also referred to as a harvesting effect, a decrease in mortality in the months afterwards.

The most severe impacts arise from multi-day heat waves, associated with high night temperatures and high relative humidity. The effects of increasing frequency, intensity and longer-lasting heat waves are regionally dampened, but in no way offset, by a reduction in relative humidity (Fischer and Schär, 2010).

In terms of health conditions, projections indicate the most severe degradation for low-altitude river basins in Southern Europe and for the Mediterranean coasts, affecting many densely populated urban centres (Figure 4.6). The effects may be further amplified due to urban heat-island effects enhancing night-time temperatures in urban areas. Consequently, the urban areas with high population densities are likely to experience the most dangerous conditions due to amplified temperatures and high air pollution.

Although climate change is expected in general to exacerbate health threats or introduce new ones, reductions in the frequency and intensity of cold extremes are expected to reduce cold-wave-related mortality.

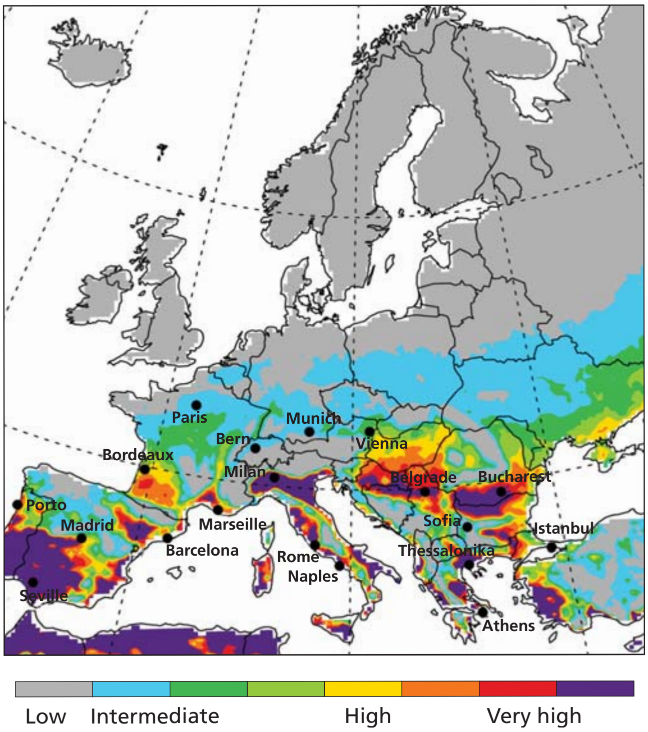
Impacts of extreme weather on other sectors

Adverse effect of climate extremes are not limited to the agriculture, energy, and health sectors, but may have consequences for the wider society. Examples include:

- transport infrastructure, vulnerable to both hot and cold extremes; flooding and avalanches;
- water supply; snow-melt and evaporation affect river runoff; flooding; contamination from parasites;
- air pollution; concentrations are often high during both persistently hot and cold extremes;
- ground pollution from flooding;
- forest and wildfires brought on by drought and heat waves;
- rapid melting of permafrost and glaciers leading to destabilisation of infrastructure in mountainous regions;
- further impacts related to changes in wind-storm events include increased vulnerability of wind-power generators and transmission lines;
- telecommunication stations may be harmed by heavy precipitation, lightning, and wind;
- shipping, fishing and the offshore industry are vulnerable to high winds and wave heights;

Figure 4.6 Change in health risk: multi-model ensemble mean of the average number of summer days exceeding the apparent temperature danger threshold

Source: after Fischer and Schär, 2010.



- finance, through the insurance sector as a result of floods, wind, lightning, hail, etc.

These illustrate the wide range of impacts across sectors. For many of these sectors, impacts, although severe, are geographically localised and limited in extent. For others, however, extreme weather can have widespread impacts at a regional or European scale, often with wider ramifications for society or the economy; two examples of these are:

Transport

The main phenomena impacting transport infrastructure have been found to be extreme precipitation and wind storms. Heavy rain can disrupt rail and road links through flooding and can also affect electricity supplies. Air transport links can be disrupted by heavy snow. High winds can bring down overhead power cables and, in extreme cases, have caused damage to bridges and viaducts. Airports may suffer closure during winter storms. Extreme heat has the capacity to damage road surfaces and distort rail lines.

Water supply

Public water-supply systems in Europe, which rely to a large extent on surface water accumulated from precipitation, are susceptible both to extremely high precipitation and to drought. Flooding of water-treatment plants is a threat to water quality while drought impacts the quantity that can be supplied.

4.6 Examples of extreme weather impacts on specific regions of Europe

The impacts of extreme weather on society and economies have been widely studied across Europe, in particular where it seems that weather patterns have changed with adverse consequences. Such studies show both where there are common features in impacts across Europe and where there are marked contrasts across the regions of Europe. They also highlight the differences that occur across geographic zones.

Across Europe, from Greece to the United Kingdom, extreme precipitation gives rise to extensive flooding, and changes in the frequency of such events would be of considerable concern to governments. Flooding can arise both from winter storms and from heavy rain in convective (summer) storms, and there are strong human factors modifying impacts. Comparative studies of impacts in different regions of Europe are important in understanding differing underlying causes responsible for similar impacts.

By contrast, geographical differences, notably between Southern and Northern Europe, can mean that extreme weather phenomena have very different impacts. The fairly recent occurrences of forest fires in Southern Europe, notably in Greece, appear to be a specific regional response to long periods of dry weather.

Climate change consequences for Southwestern Europe

In 2002 Portugal was the first South European country to publish an integrated and multi-sector assessment of vulnerabilities, impacts and adaptation (VIA) to climate change, including the impacts on water resources, coastal zones, agriculture, human health, energy, forests, biodiversity and fisheries (SIAM, 2002). This study was updated and extended to the Portuguese archipelagos of Azores and Madeira in 2006 (SIAM II, 2006). The SIAM project is a national and international reference for a multi-sector approach when assessing the impacts of and adaptation measures to climate change based on GCM climate scenarios and the downscaling of the IPCC's *Special Report on Emission Scenarios* (SRES) socio-economic scenarios. Since publication of the two SIAM reports, there has been an increased awareness of the challenges of climate change by different stakeholders and decision makers in Portugal. These have led to various VIA studies and assessments carried out by municipalities and by private and public organisations.

A VIA climate change assessment for the island of Madeira, based on an approach similar to the one used in the SIAM project, was conducted for the regional government, taking specifically into account the impacts on water resources, forests, biodiversity, energy and human health (CLIMAAT II, 2006; Cruz *et al.*, 2009). The future climate scenarios for the island were calculated using a convective model forced by the island orography and coupled to a GCM (Santos *et al.*, 2004). It was not possible, however, to make reliable projections regarding the very destructive flash floods that often affect the island, due in part to insufficient historical climate data for the very rugged territory. The last flash flood occurred on 20 February 2010, with 185 mm of rain falling in one day at Pico do Areeiro, leading to 47 deaths and widespread damage in Funchal, the island's capital and main town. The most dramatic flash flood occurred in Funchal on 9 October 1803, with an estimated 1 000 victims.

BOX 4.5 EWENT AND BALTEX

A European project called EWENT[10] has identified a range of weather hazards and vulnerabilities for the European transport system in general, including road, rail, short-shipping, and aviation. One finding was: '*the risks and current risk management systems vary considerably throughout Europe according to the transport mode and the climate zone in question*'. Extreme cold spells can damage infrastructure, and in this respect, one beneficial aspect of a future warming is the reduced occurrence of damaging cold spells.

The BALTEX[11] project, on the other hand, has focused on the Baltic Sea drainage basin and a wider range of sectors, where important elements have included the water and energy cycle, climate variability and change, water management and extreme events, and related impacts on biogeochemical cycles. The project produced an assessment of regional climate change and its impacts on the Baltic Sea basin – from hydrological to biological and socio-economic. The project work also involved a further development of regional physical climate models and the integration of biogeochemical and ecosystem models.

One of the major findings of the CLIMAAT II Project (CLIMAAT II, 2006) was a warning about the increase in the risk of dengue fever on Madeira. The insect vector, *Aedes aegypti,* was introduced in 2004 at Funchal and the warming climate was becoming more conducive to its development. Recommendations were made to monitor and control the population of *Aedes aegypti* in Madeira. Nevertheless, dengue appeared at the beginning of October 2012 and the number of infected persons reached more than 1 800 within less than two months.

Other general regional impacts

High latitudes and altitudes

Extreme events may have a complex nature, where several conditions, which by themselves may not necessarily be regarded as extreme, combine to produce a complex extreme event. One example is freezing rain, where rain is formed in warmer air layers aloft and falls on to a cool surface and freezes, which is often associated with a warm front or strong temperature inversion. Freezing rain and glaze on a large scale is sometimes called an ice storm, and

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[10] http://ewent.vtt.fi/

[11] http://www.baltex-research.eu/

is more common over North America. For example, the January 1998 Ice Storm of the Century covered the ground surface of Ontario, Quebec and New Brunswick with 7–11 cm of ice, and led to the collapse of trees and transmission lines, utility poles and transmission towers. It became the most expensive natural disaster in Canada up to that time. This event took place despite the relatively warm winter, the second-mildest on record.

Freezing rain and rain on snow can also present other problems. for example, for reindeer, impacting their grazing in Northern Fennoscandia (Vikhamar-Schuler and Hanssen-Bauer, 2010a, 2010b; Vikhamar-Schuler *et al.*, in review). Frequent freezing and thawing events can create ground motion, affecting built structures. Isaksen *et al.* (2007) reported extreme near-surface permafrost warming resulting from a remarkable temperature anomaly during winter and spring 2005–2006 on Svalbard. Such events are more likely when the surface temperature is near freezing and near-zero events have become more frequent in most non-coastal parts of Norway, especially in cold areas (Dyrrdal *et al.*, 2012). Furthermore, thawing permafrost may result in emissions of methane from organic matter stored frozen in the ground and in methane hydrates (Kvenvolden, 1988; Walter *et al.*, 2012).

There is also a higher risk that positive trends in snowfall variables and near-zero events will produce increased frequency of snow avalanches in cold areas. More frequent near-zero events along with more heavy rainfall might also trigger a larger number of rockfalls and rock slides due to decreased rock stability (Dyrrdal *et al.*, 2012).

Economic impacts and insured losses: natural catastrophes in Europe – trends of loss-relevant extreme weather events

In order to understand the economic scale of impacts of extreme weather events, the authors have considered information on the scale of losses from insurance industry records. There are several sources of insurance industry data, and for the purposes of this report the Munich Re NatCatSERVICE database has been used.

Munich Re has been analysing natural hazards and the losses they cause for more than 35 years. For this purpose, Munich Re has set up NatCatSERVICE, the most comprehensive of the three existing global natural catastrophe databases (Sigma/Swiss Re, EmDat/CRED). The Munich Re NatCatSERVICE currently comprises about 30 000 data sets of specific loss events caused by a range of natural hazards. It documents, on a global level, major events starting in 1950 and all known loss-related events from 1980 onwards, providing information on their effects on national economies, the insurance sector and the population. A stringent quality-control system assures high reliability.

Data management at Munich Re NatCatSERVICE – methodology

Events data

All loss events caused by natural hazards resulting in property damage and/or bodily injury are recorded in NatCatSERVICE. The objective of an entry in the database is to describe a catastrophe in as much detail as possible. A full entry record consists of up to 200 attributes, but the following are the most important: date and duration, category/type of peril, geographical information and humanitarian and monetary impact.

Catastrophe classes

Depending on their monetary or humanitarian impact, the documented events are put into six classes, ranging from a natural occurrence with small economic impact to a great natural catastrophe. Great natural catastrophes, at the upper end of the scale, constitute event class 6. In line with definitions used by the United Nations, a great natural catastrophe overstretches the affected region's ability to help itself, and inter-regional or international assistance is consequently required.

As a rule, this will be the case when thousands are killed and hundreds of thousands are made homeless or if the overall loss reaches exceptional dimensions, depending on the economic capacities and conditions of the country concerned. These great natural catastrophes can be used in long-term analyses starting in 1950 since such major disasters have always been reported in detail and the analysis is not distorted by a reporting bias. In Table 4.2 the six classes of loss events plus class 0, a natural extreme event without significant losses, are defined.

Categorisation of perils

The data are classified according to the perils into four hazard families – geophysical, meteorological, hydrological and climatological – each of which is further subdivided into main events and sub-perils (Table 4.3).

Table 4.2 Definitions of intensity classes of natural disasters
Source: Munich Re NatCatSERVICE database.

Catastrophe classes		Loss profile	Overall losses US$ million				and/or fatalities
			1980s*	1990s*	2000s*	2010	
0	Natural event	No property damage	–	–	–	–	none
1	Small-scale loss event	Small-scale property damage	0.63	0.91	1.18	> 1.33	1–9
2	Moderate loss event	Moderate property and structural damage	5.08	7.28	9.40	> 10.60	> 10
3	Severe catastrophe	Severe property infrastructure and structural damage	29	42	54	> 61	> 20
4	Major catastrophe	Major property, infrastructure and structural damage	114	164	212	> 230	> 100
5	Devastating catastrophe	Devastating losses within the affected region	305	437	504	636	> 500
6	Great natural catastrophe 'GREAT disaster'	Region's ability to help itself clearly overtaxed, interregional/international assistance necessary, thousands of fatalities and/or hundreds of thousands homeless, substantial economic losses (UN definition). Insured losses reach exceptional orders of magnitude					

* decadal average

Economic and insured losses
The Munich Re NatCatSERVICE database focuses on financial losses. Losses are subdivided into two categories: insured losses and economic losses. Figures for insured losses are the more reliable because they reflect claims actually paid by insurance companies. Economic losses, moreover, are more complex to assess. It is important to differentiate between direct losses, indirect losses and secondary/consequential losses. As a rule, the assessment of overall losses in NatCatSERVICE consists of direct (tangible) losses plus, in the event of business interruption, the resulting indirect losses.

Sources and data quality
The NatCatSERVICE employs around 200 sources that have been identified as first-rate for a particular region and/or type of event. The groups of main sources are:

- insurance industry information;
- meteorological and seismological services;
- reports and evaluations by aid organisations or NGOs, governments, the EU, the UN, the World Bank and other development banks;
- scientific analyses and studies;
- news agencies.

Despite first-class sources, the analysis process is subject to occasional problems. Typical challenges include false reporting, the use of incorrect conversion factors and double counting of casualties. Such data are often copied and further disseminated. The validation process in the NatCatSERVICE database checks the quality and number of the sources referred to as well as the plausibility of the loss figures and the descriptions of the event. An evaluation system has been developed for this quality check, which assigns every data record to a quality level on a scale from 1 (very good) to 6 (inadequate). Data records on quality level 4, 5 or 6 do not meet with the quality standards of the database and are not used for analyses.

Table 4.3 Categorisation of perils in hazard families and sub-perils
Source: Munich Re NatCatSERVICE database.

Hazard family	Main event	Sub-peril	
Geophysical	Earthquake	Earthquake ‘ground shaking’	
		Earthquake ‘fire following’	
		Tsunami	
	Volcanic eruption		
	Mass movement (dry)	Subsidence	
		Rockfall	
		Landslide	
Meteorological	Storm	Tropical storm	Hurricane, typhoon, cyclone
		Extratropical storm	Winter storm, blizzard, snowstorm
		Convective storm	Severe storm, thunderstorm, tornado, hailstorm
		Local storm (orographic storm)	i.e. Foehn, Bora Bora Mistral
Hydrological	Flood	General flood	
		Flash flood	
		Storm surge	
		Glacial lake outburst flood	
	Mass movement (wet)	Subsidence	
		Avalanche	
		Landslide	
Climatological	Extreme temperature	Heat wave	
		Cold wave/frost	
		Extreme winter conditions	
	Drought		
	Wildfire	Forest fire, bush fire grassland and brush fire	

Major finding of loss analysis

Since the 1980s the frequency of weather-related catastrophes worldwide has increased significantly. In the period 1980–1989 an annual average of 335 events was recorded, this rose to 545 events in the 1990s and to 716 events for 2002–2011. The relative trends for each natural peril worldwide since 1980 reveal that heat waves, droughts, wildfires and floods show the most pronounced upward trend, followed by storms (Figure 4.7).

There has been a clear distinction between all weather-related perils and geophysical disasters like earthquakes and tsunamis. The latter show only a slight increase, which is most probably driven by socio-demographic factors like population growth and the growth of settlements in risk-prone areas. Thus today a small earthquake is classified as loss-relevant, while some decades ago, because fewer people were affected or property of lower values was at stake, such an earthquake might not have been considered loss-relevant.

The situation in Europe compared to the other continents
Compared to other continents, the increase in loss-relevant natural extreme events in Europe has been only moderate (Figure 4.7). The largest increases have occurred in North America, Asia and Australia/Oceania

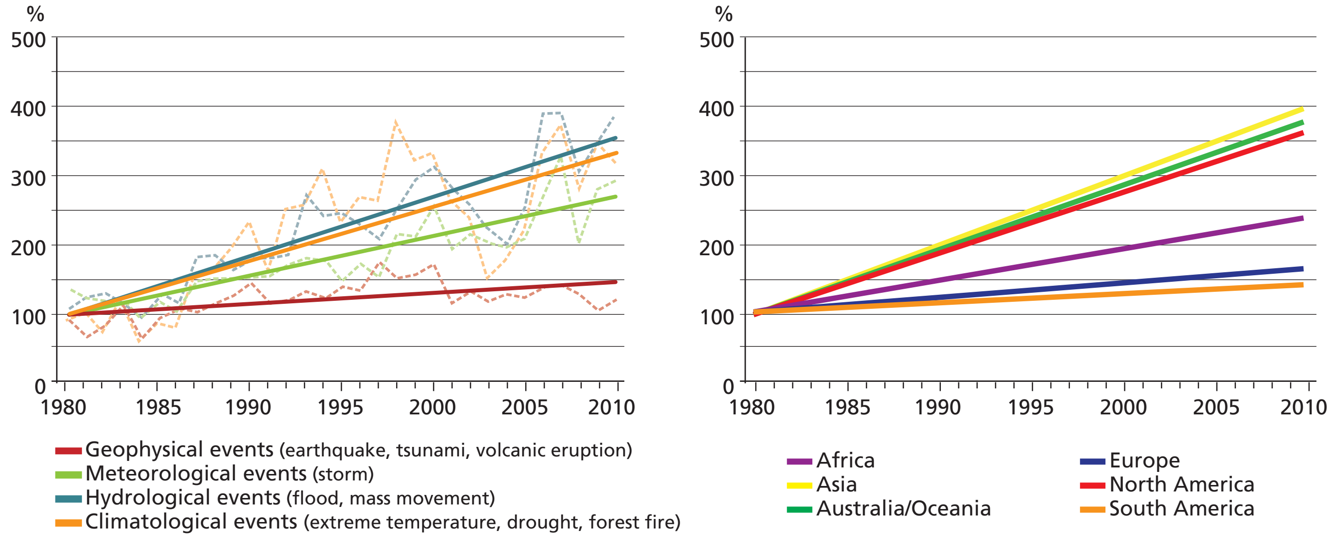


Figure 4.7 Relative trends of loss-relevant world-wide natural extreme events by peril group 1980–2010 (left) and relative trends of loss-relevant natural extreme events by continent 1980–2010 (right)

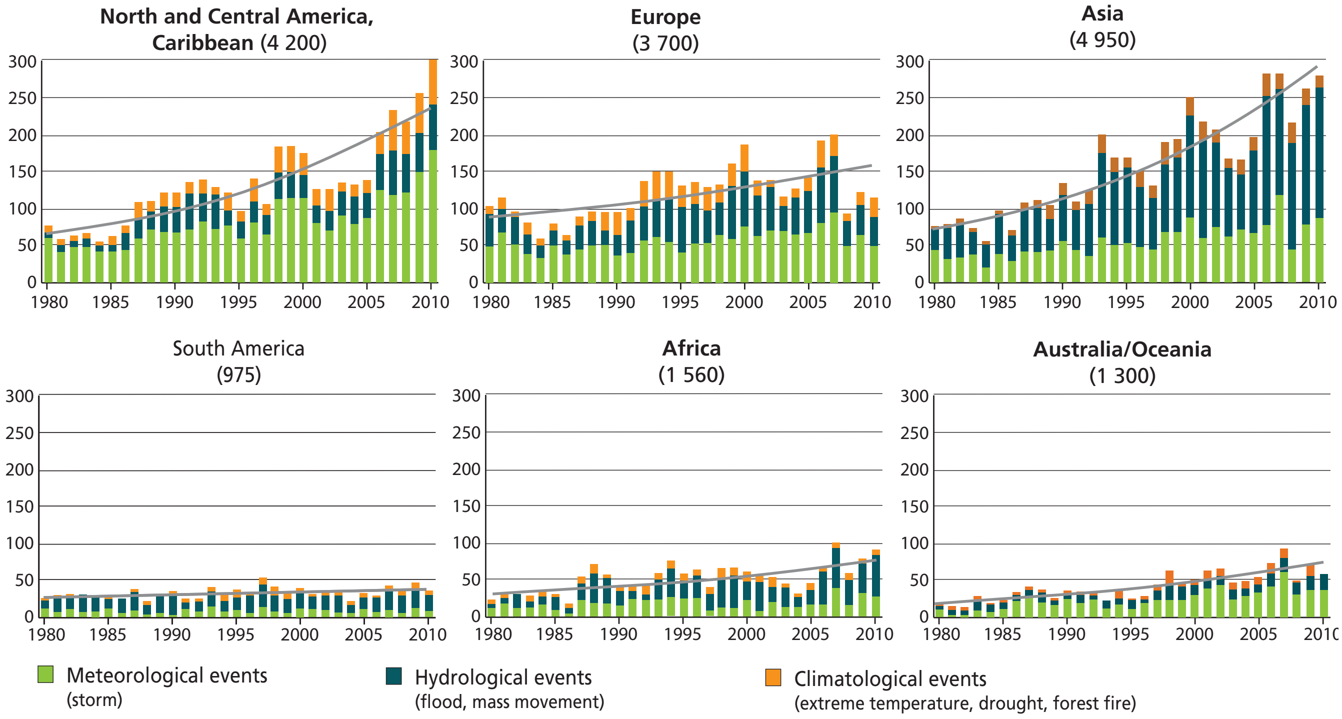
Source: Munich Re.

with today about 3.5 times as many events as at the beginning of the 1980s. In Europe there has been an increase of about 60 %.

As weather-related events have been the major drivers of these trends in all continents, there is a similar picture if geophysical events are excluded and only weather-related events considered (Figure 4.8). For the whole period, with about 30 % of all events, Asia has been hit hardest, followed by North America with about 25 %. Europe ranks third with around 22 %. The largest increase, as measured by the slopes of the calculated regression curves, has occurred in Asia with 3.9 times as many events as in the early 1980s, followed by Australia/Oceania where events increased by a factor of 3.8, and North America with a factor of 3.7.

Figure 4.8 Annual numbers of loss-relevant weather events world-wide 1980–2010, by continent

Source: Munich Re.



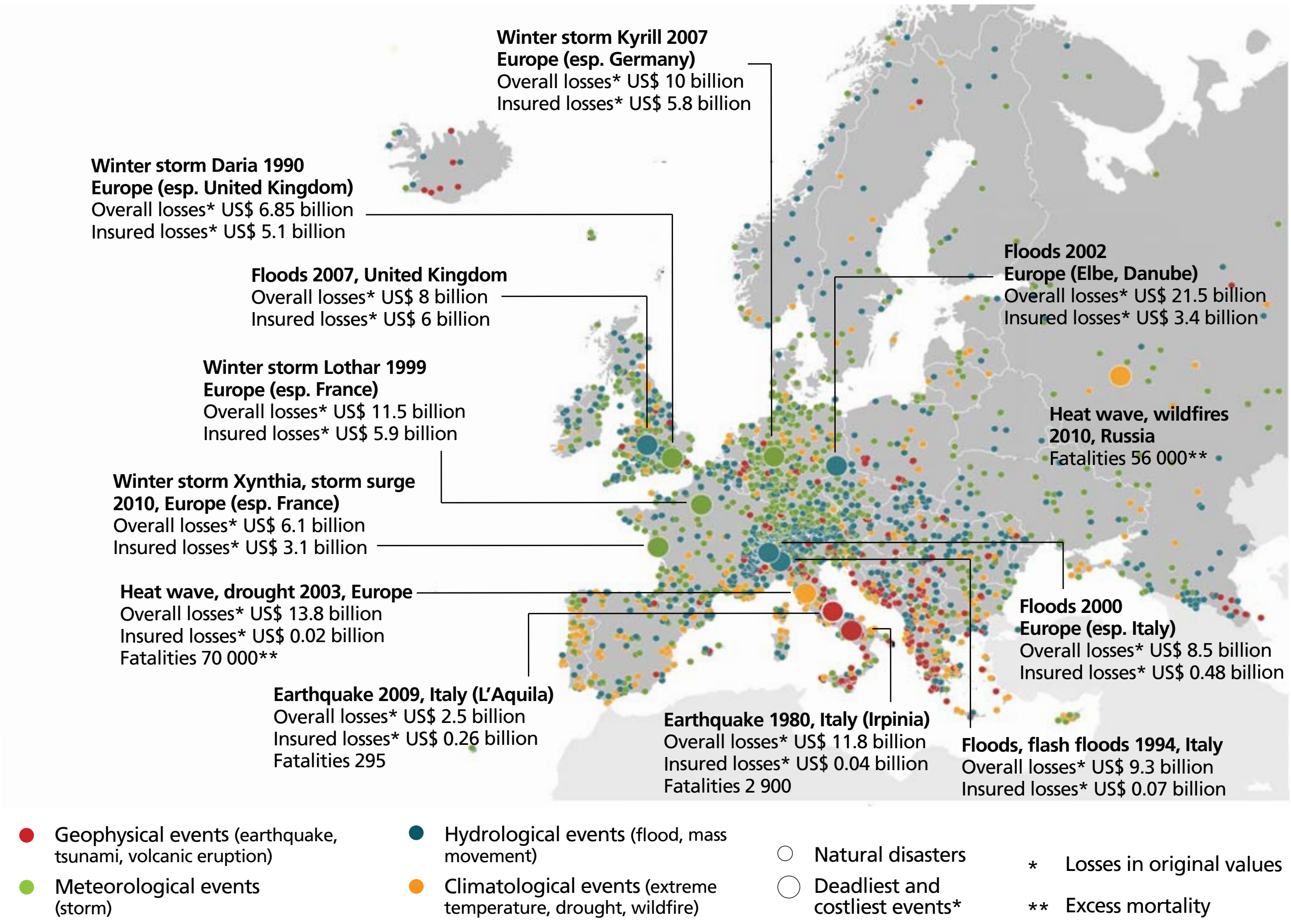


Figure 4.9 Distribution of loss-relevant natural extreme events in Europe 1980–2010

Source: Munich Re.

The increase in the number of loss-relevant weather extremes in Europe has been relatively moderate, with an increase of 70 %, a factor of 1.7, in the last 32 years. In the southern hemisphere the absolute number of loss events has been significantly lower, mainly because exposure of humans and values of property at risk are lower. There are however significant increases in Australia/Oceania, a factor of 3.8, and Africa, a factor of 2.5, with the smallest increase occuring in South America where events increased by a factor of 1.5.

The situation in Europe

Figure 4.9 shows all loss-relevant weather-related natural events over Europe in the past 31 years (1980–2010). The map shows a high concentration of natural catastrophes in the United Kingdom and Western Central Europe and low densities in Scandinavia and Northeastern Europe. While heat waves, droughts, wildfires and earthquakes have been major perils in Southern and Southeastern Europe, it is floods and storms that have caused relevant losses in Western and Central Europe. In Southwestern Europe, heat waves, droughts and wildfires are the major perils.

In the NatCatSERVICE database 4 100 natural loss events in Europe have been registered since 1980. Of these, 91 % were attributable to weather-related phenomena, 41 % to storms of all kinds, 34 % to floods and 16 % to heat waves, droughts and wildfires (Figure 4.10). In Southern Europe the distribution is different, a 10 % higher proportion of heat waves, droughts and wildfires (26 %) but a significantly lower proportion of storms (27 % instead of 41 %). The European economies have been confronted with a total natural catastrophe economic loss burden of € 415 billion (in 2010 values). The most costly perils have been storm and flood events. Storms and floods each accounted for 35 % of all direct economic losses, equivalent to € 145 billion each. The insured losses for all kinds of perils amounted to € 130 billion. Due to the high insurance penetration for storms, these kinds of meteorological

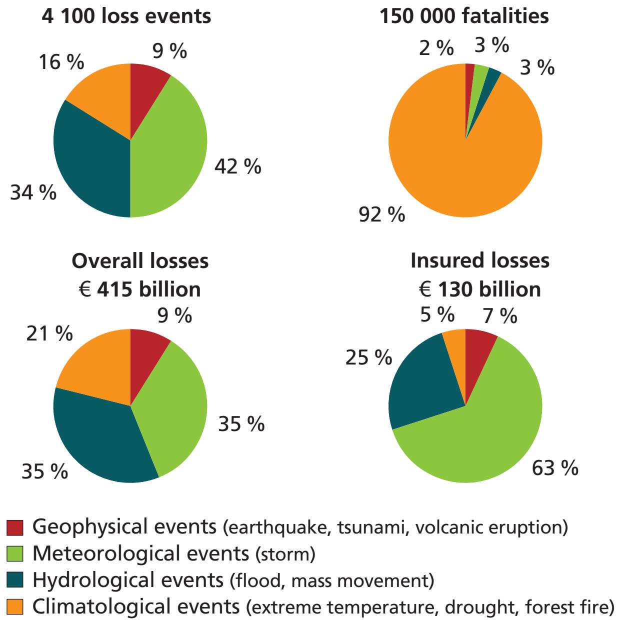


Figure 4.10 Distribution of extreme events, fatalities, total and insured losses in Europe in respect of the different groups of natural perils 1980–2010

Source: Munich Re.

events accounted for roughly two-thirds of this, € 82 billion. Losses are not limited to property and infrastructure; since 1980, around 150 000 lives have been lost due to natural disasters: 92 % of these have been caused by climatological events, predominantly heat waves. The two heat waves of 2003 in Central Europe and 2010 in Russia alone claimed 126 000 lives.

On a global basis tropical cyclones are the costliest weather related disasters, but in Europe the most costly single disasters since 1980 were the 2002 floods in Central and Eastern Europe causing an overall loss of € 16.5 billion, followed by the heat wave of 2003 € 12.2 billion loss, and the winter storm Lothar in December 1999, € 11.5 billion loss (Table 4.4 and Box 4.6). The annually aggregated losses in Europe are heavily dominated by single events that normally cause damage in several countries simultaneously, which was the case in the three costliest events mentioned above. In the list of the ten most costly natural disasters in Europe, there are only two geophysical events, two earthquakes in Italy, in 1980 and 1997. The most prevalent perils in the list are four floods followed by three winter storms and one heat wave.

The countries most affected by natural disasters in Europe since 1980 have been Germany with 455 events, France with 425, United Kingdom 415, Switzerland 360, Italy 355 and Spain 317 (Table 4.5). Germany has also been the country with the highest overall (€ 68 billion) and insured losses (€ 29 billion). Overall losses in France, the United Kingdom and Italy have been in the region of € 60 billion, of which 47 % were insured in France, 65 % in the United Kingdom, but only 3 % in Italy.

The largest increase in the frequency of weather-related loss events since 1980 occurred in Germany with a 200 % increase in the number of events. The second and third largest increases were in Spain, 120 %, and Switzerland, 110 %. The increases in France, 30 %, United Kingdom, 30 %, and Italy, 10 %, were comparably low (Figure 4.11).

Increases in the frequency of weather-related loss events are also expected to result in rising economic and insured losses. Figure 4.12 shows the trends of total economic and insured losses in Europe caused by extreme weather events. All values have been adjusted for inflation and represent 2010-equivalent Euros.

Annual total economic losses have increased by about 50 % since 1980 from about € 8 billion to € 12 billion. This increase of 50 % is a little lower than the increase in

BOX 4.6 MAPPING NATURAL HAZARDS

EEA Technical report No 13/2010, *Mapping the impacts of natural hazards and technological accidents in Europe. An overview of the last decade* rated the events resulting in the largest overall losses. For floods the events were (1) Central Europe (2002, more then € 20 billion) (2) Italy, France and the Swiss Alps (2000, about € 12 billion), and (3) in the United Kingdom (2007, more than € 4 billion). For earthquakes the top two events were Izmit, Turkey (1999, more than € 11 billion) and L'Aquila, Italy (2009, more than € 2 billion). For winter storms, Central Europe was hit in December 1999 causing more than € 18 billion worth of damage and in January 2007 causing almost € 8 billion of damage.

Table 4.4 The 10 costliest natural catastrophes in Europe 1980–2010

Source: Munich Re NatCatSERVICE database.

			Losses € million, original losses		
Period	**Event**	**Affected area**	**Overall**	**Insured**	**Fatalities**
12–20 August 2002	Floods, severe storm	Germany, Austria, Czech Republic Hungary, Moldova, Slovakia Switzerland	16 800	3 500	30
July–August 2003	Heat wave, drought	France, Germany, Italy, Portugal Romania, Spain, United Kingdom	12 300	18	70 000
23 November 1980	Earthquake	Italy: Irpinia, Basilicata, Potenza Salerno, Benevento, Naples	11 800	40	2 900
26 December 1999	Winter storm Lothar	France, Germany, Switzerland, Belgium, Austria	11 500	5 900	110
13–20 October 2000	Floods, landslides	Italy: Aosta valley, Piedmont, Lombardy, Emilia Romagna; Switzerland: Walais, Ticino; France	10 000	570	38
18–20 January 2007	Winter storm Kyrill	United Kingdom, Germany, France, Netherlands, Belgium, Denmark, Austria	7 800	4 500	49
4–6 November 1994	Floods, flash floods	Italy: Piedmont, Lombardy Liguria, Aosta valley, Emilia Romagna	7 500	52	68
25–26 January 1990	Winter storm Daria	Belgium, Denmark, France, Germany, Ireland, Netherlands, Sweden, United Kingdom	5 900	4 400	94
5 July–10 August 1997	Floods	Poland, Czech Republic, Slovakia, Germany, Austria	5 500	750	118
26 September 1997	Earthquake	Italy: Umbria, Assisi, Cellecurti Cesi, Nocera, Umbria, Foligno, Perugia	5 400	5	11

the number of events. The annual insured losses increased by 230 % from € 1.5 billion to € 5.0 billion, most probably also driven by an increasing insurance penetration.

In Figure 4.13 the specific trends for Europe in the numbers of loss-relevant geophysical events, storms and floods are shown for the last 31 years. There has been a clear contrast between events originating in the Earth's crust and those originating in the atmosphere. While there has even been a slight decrease of geophysical events, storm and flood losses have become significantly more frequent in Europe. Storm events increased by 75 % from 40 to 70, and flood events doubled from 30 to 60. Climate change does not directly influence geophysical events but is known to be a factor in storms and floods, and these trends are consistent with the proposition that climate change is a primary driver of natural catastrophe losses.

Expected future economic impacts

According to the *IPCC Fourth Assessment Report* (Solomon *et al.*, 2007), global warming will result, in many regions, in increases in the frequency and intensity of weather extremes. In a recent study commissioned by the German Association of Insurers (GDV) the future insured losses caused by storms and

Table 4.5 Countries in Europe with the largest number of loss events 1980–2010

Source: Munich Re NatCatSERVICE database.

Country	Number of loss events	Overall losses € billion 2010 values	Insured losses € billion 2010 values
Germany	420	68 000	29 000
France	410	55 000	25 000
United Kingdom	400	55 000	34 000
Italy	350	57 000	1 500
Switzerland	350	16 000	7 000
Spain	300	33 000	4 000

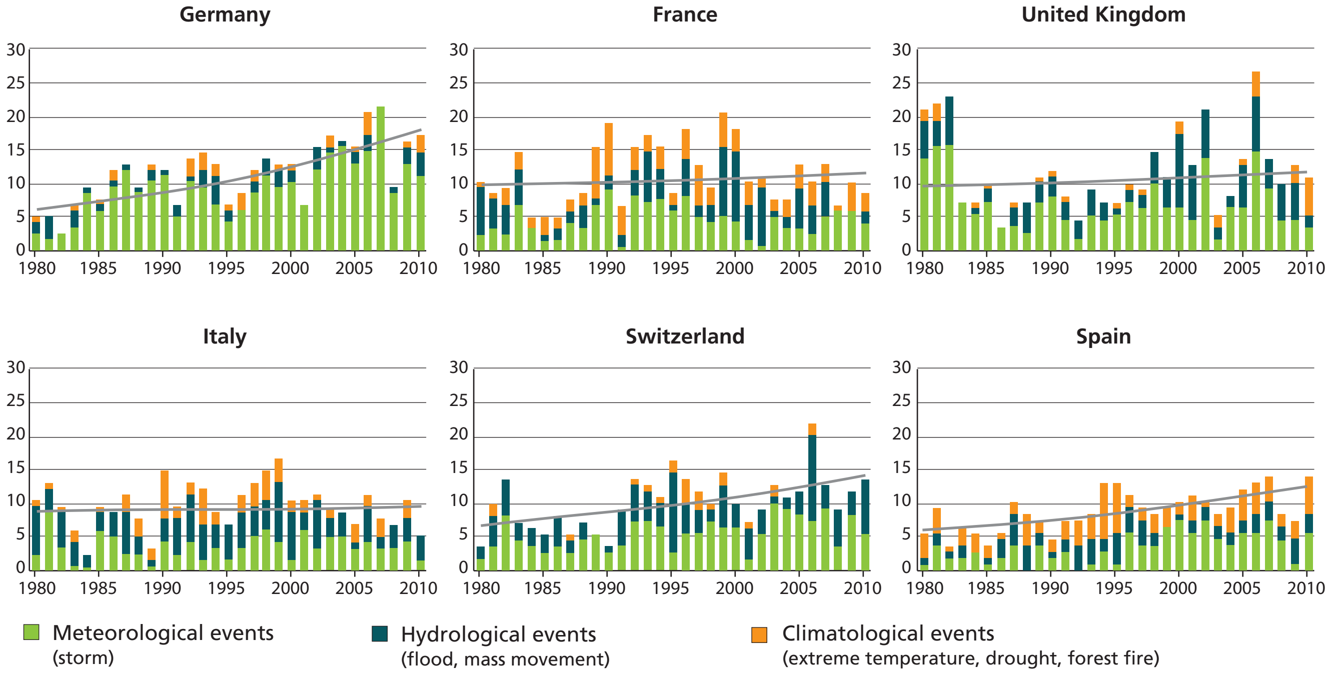
floods have been modelled on the basis of the current property insurance portfolio in Germany with a wide range of global and regional climate models. Preliminary results were presented to the public in May 2011 at a conference in Berlin. The results are very robust, all model runs have shown future increases in insured losses caused by climate change.

For example, it is expected that the losses caused by convective storms in the summer will increase by 25 % on average over the next 30 years, and for the period 2041–2070 they are expected to increase by 61 % (Figure 4.14). Flood events causing losses of € 750 million, which are currently expected every 50 years, will become about 20-year events within the next 30 years. The GDV study focused on Germany, but as weather extremes are not confined to political borders it can be assumed that similar effects will occur at least in the neighbouring countries, if not in the whole of Europe.

As the results of the GDV study clearly show the causal relation between loss trends and climate change, and with the assumption that such changes will be driven by a continuous process rather than one that starts suddenly in

Figure 4.11 Trends in numbers of loss-relevant extreme weather events in the six most affected countries in Europe 1980–2010

Source: Munich Re.



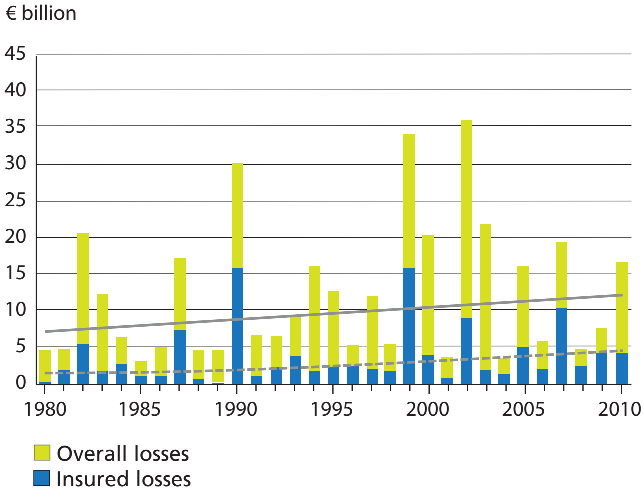


Figure 4.12 Annual total economic and insured losses caused by extreme weather events in Europe 1980–2010
Source: Munich Re.

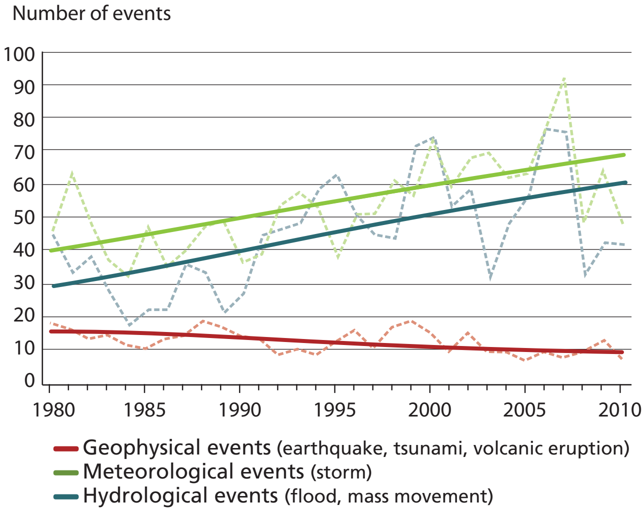
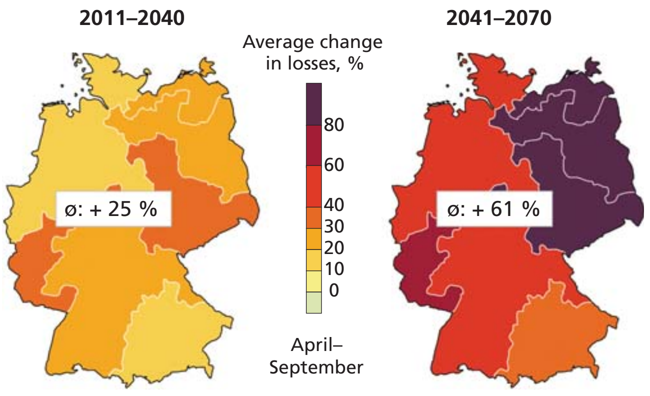


Figure 4.13 Trends in loss-relevant geophysical events, storms and floods in Europe 1980–2010
Source: Munich Re.

the next few years, there is a strong suggestion that part of the loss trends already detected in Germany, and also most probably in many parts of Europe, can be attributed to climate change.

In conclusion, the Munich Re NatCatSERVICE data clearly show that the number of loss-relevant weather extremes has increased significantly globally and also, to a smaller but still relevant degree, in Europe. There is growing evidence that at least part of this increase is driven by global warming. Some of the hazard-driven increases in loss events may have been offset to some extent by human activities, for example through loss prevention measures. There is probably such a confounding factor in the flood-loss data since these can be influenced much more than wind-storm losses by preventive measures. So, for example, since the large-scale flood in Hamburg in 1962, with economic losses in the range of € 1.6 billion (in 2010 Euros) and 347 fatalities, more than € 2 billion have been invested in flood-protection measures. Since then the level of the river Elbe has reached even higher levels four times without causing significant losses. So in this case the loss trend points downwards while the weather-driven hazard has increased.

Figure 4.14 Forecast of climate-change-driven insured losses caused by storms in summer in Germany in the next 30–60 years
Source: German Association of Insurers (GDV).



Statistical loss model for storm/hail: regional distribution of changes in losses in an A1B-scenario relative to the average of the past 25 years

Evidence from other sources

The SREX report (IPCC, 2012) also observes that droughts are a major source of losses in Europe, resulting in larger economical losses than floods or earthquakes in the Mediterranean region. Water shortages arising from droughts will affect hydroelectric generation, tourism, forestry and natural ecosystems. The risk of wildfires is heightened during drought conditions, although the SREX report notes that an increase in dryness does not translate directly into increased fire occurrence or changes in vegetation.

In the case of coastal flooding, areas presently at risk will continue to be at risk in the future. The projected sea-level rise is expected to result in land loss, salinisation of soil and groundwater, and damage to property and infrastructure. The Netherlands is considered particularly susceptible to both sea-level rise and coastal flooding.

The impacts of weather and climate extremes are to a large degree determined by exposure and vulnerability. Economic losses from weather- and climate-related disasters have increased, albeit with large geographical and year-to-year differences. The SREX report concludes that increases in economic losses are influenced by an increasing exposure of people and economic assets, and that it is difficult to find a link to climate change for long-term trends in economic disaster losses, when adjusted for wealth and population increases. However, the SREX report does not exclude the possibility that climate change has had an influence.

According to the SREX report, there is a high confidence that changes in climate will have the potential to cause serious effects on water management systems, although climate is only one of several factors. In some regions, climate change may not be the most important driver. The report also attributes high confidence to the conclusion that climate change has the potential to cause substantial food losses in critical regions.

Heat waves can directly reduce the production rate in ecosystems through water shortage and constraining both carbon and nitrogen cycling. In the most extreme heat waves, natural ecosystems change from being a carbon dioxide sink and become a source. Indeed, a 30 % reduction in gross primary productivity together with decreased ecosystem respiration over Europe during the heat wave in 2003 resulted in a strong net source of carbon dioxide to the atmosphere, and reversed the effect of four years of net ecosystem carbon sequestration. Both gross primary production and total ecosystem respiration decreased in 2003 in many regions of Europe. In the worst case, heat waves result in species mortalities.

The SREX report notes that, where climate change alters the frequency and severity of extremes, some infrastructure may become inadequate. The capacity of drainage and sewage systems, for example, may be overwhelmed by the increase in heavy rainfall, and power lines and supply may be vulnerable to changes in storm activity – for example, the Lothar and Martin storms in 1999 devastated the French electricity-supply network. Telecommunication may also fail during storms, and recent events in Scandinavia have shown that mobile phone networks can be vulnerable.

It is expected that climate change will affect coastal infrastructure and logistic systems, with implications for international trade. In particular, terminals, intermodal facilities, freight villages, storage areas and cargo can be affected by coastal inundation due to storm surges and river floods. Water supply may be contaminated by spill water and flooding from extreme precipitation, and severe droughts may affect power plants' supply of cooling water. When it comes to roads, bridges and culverts are expected to be most vulnerable if precipitation amounts become more extreme. Extreme temperatures may also impose additional stresses on steel constructions, such as in bridges, roads and railways, although some construction is replaced every 20 years and can accommodate climate change at the time of replacement. Coastal regions will become more at risk to combinations of storm surge, high tides, and sea-level rise. Built infrastructure with light materials such as lightweight roofs used for warehouses are less able to withstand strong winds and increased snow loads, and changes in precipitation and humidity can cause damp problems in houses.

CHAPTER 5 ADAPTATION TO EXTREME WEATHER PHENOMENA AND RISK REDUCTION

5.1 Introduction

In many sectors of the economy, adaptation to extreme weather has been part of planning processes over many years. Current energy and transport infrastructure, for example, have developed considerable resilience to extreme precipitation and consequent flooding. In part this has been a commercial or operational response to the experience of past extreme events and in part the need to plan for resilience.

Assumptions about future operating conditions are a normal part of planning, and definition of the future climate is crucial to the design process. It is clearly desirable in future investment to build in a degree of resilience, but resilience comes at a cost. There is a balance to be struck between the degree of resilience and affordability, for example of large infrastructure projects, and a project assessment may include a level of acceptable risk. In general such risk is carefully considered and the consequences of failure may be considered acceptable, even if highly undesirable. Yet despite careful planning, there are instances when conditions exceed planning assumptions and damage beyond the acceptable level occurs, for example in widespread flooding.

The crucial factor in planning is the frequency of such instances and their severity. For planning purposes it is crucial to understand whether such instances will occur as in the past or whether there is a trend towards more or/and more severe instances. Climate data is therefore a crucial input to the planning processes of a wide range of economic sectors. Box 4.5 describes European research designed to improve understanding of impacts of extreme weather on different sectors of the European economy at European and regional scales. Impacts of extreme weather on the energy and health sectors are discussed in Chapter 4, with some of the key extreme weather phenomena that affect other sectors and the nature of the impacts. The consequences of this for adaptation are outlined in this chapter.

Adaptation to climate change is the action and behaviour employed by individuals, communities, companies and societies to reduce the harmful impacts of change or to optimise the benefits that might come from it. The need for an organised approach to adaptation has been widely recognised by national governments and regional bodies, including the European Union. The main approach taken by public administrations has been to develop plans and strategies for improving resilience to change, with a focus on strategic areas where government action is appropriate. There is widespread recognition that adaptation action of non-governmental actors is crucial to national and regional resilience, and the role of government has been seen as an enabling one, ensuring that frameworks are in place to monitor states of preparedness, for example of key infrastructure such as power or transport, and that key information is available and accessible. Adaptation strategy, therefore, has a geographical dimension, with for example national adaptation plans, so that it can be focused on specific risks, as in flood-risk management plans, and it has a sectoral dimension, with different sectors within economies, including businesses and public organisations, developing sectoral adaptation plans.

The World Bank has characterised the key steps in the development of an adaptation strategy (Box 5.1) and these include the assessment of climate risk. Much of the detailed assessment of climate risk done so far has focused on the long-term trends of average climatic conditions but there has recently been significant

BOX 5.1 ADAPTATION PLANNING

World Bank Adaptation Guidance Notes

Key stages in adaptation planning:

- identify and engage institutions;
- engage local communities;
- assess climate risk;
- strengthen capacity and policy frameworks;
- promote and enable institutional environment;
- identify adaptation measures;
- evaluate via economic analysis;
- monitor and evaluate activities.

development in the understanding of climatic extremes. In the previous chapters, we have considered the evidence available about past and future patterns of extreme weather and the impacts these are likely to have. In this chapter we consider how these changes in extremes bear on requirements for adaptation and possible responses at different geographic scales within plans for managing specific risks and across different economic sectors.

Current research shows that a transition from the current lack of appropriate legislation is required for adaptation to climate change to move from the arena of special interests and become mainstream in society (Pelling *et al.*, 2008; Dannevig *et al.*, 2012).

The same authors refer to studies that show that the occurrence of climate-related natural hazards can serve as focusing events for reactive adaptation policies. As adaptation to future climate is currently to a large extent, due to the lack of legislation, a voluntary undertaking, policy makers do not have to take appropriate action. Dannevig *et al.* (2012) refer to how institutions, self-organisation, social learning and social capital influence the ability of organisations to adapt to climate change. Social learning is the capacity and processes through which new values, ideas and practices are disseminated, popularised and become dominant in a society or an organisation (Pelling, 2011, in Dannevig *et al.*, 2012). Informal networks of NGOs, academics and officials can facilitate social learning. Furthermore, Pelling (2011), quoted by Dannevig *et al.* (2012), found that organisations are the principal barriers to adaptation to climate change where regulations and standards do not reflect the impacts of climate change, where past examples of climate adaptation are lacking and where senior management support for the development of adaptation plans is limited.

Another question is why adaptation is becoming a topic of interest in organisations and local government in the first place. What sets their agendas? Dannevig *et al.* (2012) define four factors that contribute to agenda-setting in the context of climate change and adaptation: individual efforts, focusing events, real world indicators, and external expertise.

Individual efforts relate to engaged officials or institutional capacity. Focusing events relate to local impact of extreme weather such as floods or mudslides that change awareness abruptly – such events are commonplace in most countries in Europe. Real-world indicators relate to recurring problematic conditions, such as minor flood events or high-impact weather conditions. External expertise takes place through the involvement of municipalities or organisations in relevant research projects.

Agenda setting in the context of climate change and adaptation has to take place in a social or political setting. Scientific information about changes with time in the probability distributions of extreme weather events over Europe has the capacity to inform the processes that set the required societal agenda for introducing adequate climate-change adaptation measures in Europe.

The concept of adaptation to extreme climatic events has roots going back centuries, and there are historical description of how people in the past have used precautionary principles to minimise the harmful effects of climatic variations. Indeed, in the 16th century, Niccolò Machiavelli wrote in *The Prince* about managing rivers to reduce the risk of flooding: '*I compare fortune to one of those violent rivers which, when they are enraged, flood plains, tear down trees and buildings, wash soil from one place to deposit it in another. Everyone flees before them, everybody yields to their impetus, there is no possibility of resistance. Yet although such is their nature, it does not follow that when they are flowing quietly one cannot take precautions, constructing dikes and embankments so that when the river is in flood they would keep to one channel or their impetus be less wild and dangerous*' (Machiavelli *et al.*, 2003). Hence, trends in the toll of extreme climatic events reflects both societies' responses to past events and variations in the extremes themselves, implying that meteorological measurements, such as rain-gauge data, are the more reliable source of information on questions of whether the climate and course of extreme events has changed.

When the climate changes, the old conditions to which societies have adapted are no longer the norm, and there is a need to adapt further. Public awareness about climate change is still emerging, and climate-change adaptation is still in its infancy. Material on climate-change adaptation and experience from case studies remains in short supply. There may also be a lack of openness and information-sharing due to business confidentiality and commercial competition.

The European Environment Agency (EEA, 2012) makes multiple references to adaptation, but it discusses the needs on a high and general level and does not provide many specific case examples. The EEA has published a dedicated report on adaptation (EEA, 2013), where actions to adapt to climate change at European, national and sub-national levels are assessed. The EEA report points to a number of important activities on climate-change adaptation, such as Climate-adapt and EEA resources for climate-change adaptation.

To date, only 13 of the European Economic Area countries (the EU countries plus Iceland, Liechtenstein and Norway) have national adaptation strategies, while 15 have not adopted national adaptation strategies[12]. ADAM, the EU Adaptation and Mitigation Strategies project, provides a list of adaptation options for extreme events such as drought, flooding, heat waves and sea-level rise, and an inventory of good practice measures relevant to a range of hazards and applicable in a range of contexts. The EEA Report concluded, however, that '*although our understanding of adaptation has improved in recent years, evidence (and more critically, evaluation and qualification) of the extent, feasibility, efficiency, and cost effectiveness of different options remains largely lacking*'.

A number of adaptation websites provide information from European projects about local climate change, for example those arising from the FP7 ENSEMBLES project. Such projects provide scenarios covering a range of possible outcomes, but there is a danger in placing too much confidence in the maps they provide showing future changes because the set of outcomes they consider is limited. Furthermore, it is acknowledged that the models on which these results are based have not yet matured and are still evolving (Palmer, 2011). Future generations of model simulation are expected to provide more complete information, which may differ from the present estimates to some degree. Brown and Wilby (2012) warned against reliance on estimates of local climate change, and proposed a bottom-up strategy. Downscaling for the future also involves many unknowns, although Brown and Wilby (2012) argued that it can nevertheless provide some tentative inputs to a more comprehensive approach to risk assessment based on a wide range of factors, most of which may not necessarily be related to climate. It is important to keep in mind that the analysis should be flexible so that inputs from the climate-model simulations can easily and continuously be updated with the most recent state-of-the-art results.

The local climate scenarios offered by the EEA and the ENSEMBLES project have almost exclusively highlighted regional climate models (RCMs) and neglected empirical-statistical downscaling (ESD) schemes. The RCMs and ESD strategies have different strengths and weaknesses, and there is an emerging awareness that the two approaches are complementary in many ways (Benestad, 2011). The RCM results tend to provide a more complete spatial description over a limited region, but the RCMs are computer resource-demanding and only a limited number of simulations based on different global climate models is feasible. ESD, on the other hand, requires fewer computer resources and is well adapted to large climate model ensembles, providing a better account of the range of possible outcomes, for example associated with different large-scale atmospheric flows (Deser *et al.*, 2012). For extremes, it is particularly important to get large data samples for good statistical representation of intense, rare, and irregular events. Furthermore, since the RCM and ESD approaches draw on information from different sources, it is important to include both in order to maximise the relevant useful information for tackling a problem with many unknowns.

Other resources on European climate-change adaptation include:

- The ESPON programme[13] provides pan-European evidence and knowledge about European territorial structures, trends, perspectives and policy impacts, and facilitating comparisons amongst regions and cities. The programme forms a platform for finding new opportunities for growth in the context of change due to factors that include climate change.
- *Urban adaptation to climate change in Europe* (EEA, 2012) discusses heat, flooding, water scarcity and droughts.
- The EU's White Paper *Adapting to Climate Change* provides a set of guidelines for the development of adaptation policy and measures, noting that *'adaptation will be a long and continuous process. It will operate at all levels and require close coordination with stakeholders*'.

Adaptation and risk management

Similar temperature extremes affect health differently in different parts of the EU, for example in Greece and

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[12] http://climate-adapt.eea.europa.eu/web/guest/adaptation-strategies

[13] http://www.espon.eu/main

Norway. This demonstrates that, to some extent, adaptation to temperature extremes is possible and has taken place. The IPCC 2011 *Summary for Policy Makers* (Field *et al.*, 2012) recommends the following low-regret options that reduce exposure and vulnerability:

- early-warning systems that reach particularly vulnerable groups, such as the elderly;
- vulnerability mapping and corresponding measures;
- public information on what to do during heat waves, including advice on behaviour;
- use of social-care networks to reach vulnerable groups.

Further strategies, policies, and measures include those that aim to raise awareness of heat waves as a public health concern, and of the effects of changes in urban infrastructure and land-use planning. For example increasing urban green space, changes in approaches to cooling for public facilities and adjustments in energy generation and transmission infrastructure can all contribute to reducing exposure of the public to extreme heat (Field *et al.*, 2012).

Good practice in adaptation strategies in Europe

Many of the published adaptation guidelines treat the range of different sectors that might be affected by climate change: water supply, river navigation, agriculture, forestry, civil engineering, energy and others. Most, but not all of them, identify particular extreme events that are of special concern and require targeted adaptation measures. These include wind storms, heat waves and extreme high tides or river floods, reflecting the practical experience of these events and what is known about losses (see Chapter 4). However, recommendations on specific adaptation measures for addressing changes in scale or frequency of extreme events are rarely given, probably due of the lack of clear advice on changes in these variables. At present advice on adaptation measures is given mostly in a very general way and there is clearly a requirement for better guidance on future patterns of extreme weather.

5.2 Adaptation planning at different geographic scales

Global-scale planning

Although most direct consequences of climate extremes are local and regional in character, recovery and contingency plans for dealing with these consequences often involve the global community. The clearest examples of massive international mobilisation are seen in connection with earthquakes and tsunamis, and the actions of international organisations such as the World Food Programme and the NGOs that are engaged in the relief of famines, floods and other large-scale disasters. The World Bank has established a climate-change knowledge portal and is engaged in climate-adaptation initiatives.

The geographic pooling of risks through reinsurance related to food security, trade and energy production and delivery is one approach for adapting to climate change on a global scale. Sharing of data, knowledge, research collaboration and improving forecasts on timescales of days to decades, are also important components and supplements to emergency plans and protocols.

Adaptation measures also need to be built into international agreements on the management of disasters and populations that are environmentally displaced. Such amendments to current agreements are urgently required as progress on reducing climate forcing is slow and further warming is to be expected.

A key part of adaptation strategies at all levels is the provision of high-quality information about the future conditions to which the different administrations, communities and commercial entities will have to adapt. The general term for this provision is climate services. At a global level, the WMO has played a major role in the development of climate services. At its extraordinary congress in 2012, WMO decided to implement the Global Framework for Climate Services (GFCS) (Box 5.2; http://www.gfcs-climate.org/implementation-plan).

It is important to note that the objective of GFCS is to enable society to better manage the risks and opportunities arising from climate variability and change through developing and incorporating science-based climate information and prediction into planning, policy and practice. This means that GFCS as such does not establish social or political mechanisms that foster adaptation measures to be developed and implemented. However, as GFCS is developed it will raise awareness related to adaptation needs worldwide, and thereby move these needs from the arena of special interests to become mainstream, whereby appropriate agendas will be set: individual efforts, focusing events, real-world indicators and external expertise.

BOX 5.2 GLOBAL FRAMEWORK FOR CLIMATE SERVICES

In order to prepare the global society for living with, and adapting to, climate variability and change, a global climate service has been established by the WMO. In this context, a climate service is considered to be the provision of climate information in such a way as to assist decision making by individuals and organisations globally. The service component involves appropriate engagement, an effective access mechanism and responsiveness to users' needs. Effective climate services will facilitate climate-smart decisions that will, for example, reduce the impact of climate-related disasters, improve food security and health outcomes and enhance water-resource management.

The vision of the WMO framework is to enable society to better manage the risks and opportunities arising from climate variability and change, especially for those who are most vulnerable to climate-related hazards. This will be done through developing and incorporating science-based climate information and prediction into planning, policy and practice.

The framework includes the following eight principles for guiding successful achievement of its overarching goals:

1. all countries will benefit, but priority shall go to building the capacity of developing countries vulnerable to the impacts of climate change and variability;
2. the primary goal will be to ensure greater availability, access to and use of enhanced climate services for all countries;
3. activities will address three geographic domains: global, regional and national;
4. operational climate services will be the core element;
5. climate information is primarily an international public good provided by governments, which will have a central role in its management;
6. promote the free and open exchange of climate-relevant data, tools and scientifically based methods, while respecting national and international policies;
7. the role of the framework will be to facilitate and strengthen, not to duplicate;
8. the framework will be built through user-provider partnerships that include all stakeholders.

The term climate-relevant data in Principle 6 highlights the point that many climate services need socio-economic and environmental data in addition to climate data. However, the principle of free and open exchange of climate-relevant data needs to respect national and international policies. For example, some data may need to be restricted in the light of national interests if it compromises national security, the safety of citizens or national competitiveness. In such cases national policy may enable access to these data by climate-service providers within a country's national borders.

The WMO congress decided:

1. to adopt the draft Implementation Plan of the Global Framework for Climate Services (GFCS) for subsequent consideration by the Intergovernmental Board on Climate Services (http://www.gfcs-climate.org/implementation-plan);
2. entrust the Intergovernmental Board on Climate Services with the responsibility to oversee implementation of priority activities as set out in part of the draft Implementation Plan ((http://www.gfcs-climate.org/implementation-plan, Chapter 4), with the involvement of relevant stakeholders, including other United Nations bodies;
3. to entrust the Intergovernmental Board on Climate Services with the task of regularly reviewing the draft Implementation Plan of the Global Framework for Climate Services, and to inform the subsequent session of Congress of any changes.

Europe

In the context of climate policy, the topic of adaptation emerged from the beginning of the 21st century as a policy of equal value to mitigation. In Europe, the European Environment Agency (EEA) drafted its first report on water adaptation and good practice in adaptation in 2007. Since then, all European countries have been developing their own adaptation strategies. The European Climate Adaptation Platform (CLIMATE-ADAPT), developed as a partnership between the European Commission and the EEA, aims to support Europe in adapting to climate change. It helps users to access and share data and information on the web[14]. Another resource is provided by the global community

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[14] climate-adapt.eea.europa.eu

called Climate Services Partnership (CSP)[15], which provides guidance documents and a number of case studies for the use of climate information. Although the case studies do not focus on Europe, some may nevertheless provide some useful experience regarding the use of climate information and the dialogue between data providers and end-users.

The EEA member countries are at different stages of preparing, developing and implementing national adaptation strategies. The development depends on the magnitude and nature of the observed impacts, assessments of current and future vulnerability and the capacity to adapt. All countries submitted information in 2010 on their adaptation plans as part of their 5th National Communication to the United Nations Framework Convention on Climate Change (UNFCCC). In addition, actions and measures are increasingly being taken at regional and local levels. The European Commission helps to coordinate and fund adaptation actions across its Member States, ensuring that climate change becomes a key consideration in all sectors.

In a comprehensive report by the Partnership for European Environmental Research (Swart *et al*., 2009) the governance arrangements for the adaptation strategies of 14 European countries were analysed. It is found that weather-related extreme events are among the main drivers for establishing adaptation strategies, even if many details concerning extreme events are still unknown.

An overview of progress towards national adaptation strategies is presented on the EEA website. As of 2011, 26 out of 32 member countries had presented their national adaptation strategies, climate-change action plans and other technical documents.

In addition to their adaptation plans or adaptation strategies, some EU Member States have also established web portals with more practical information, recommendations and guidelines for action (Table 5.1). Not all national web portals are listed here, because many are published only in their national language.

Many more web portals can be found, especially from smaller administrative entities (German states, counties etc.), NGOs or other private initiatives. The European Commission helps to coordinate and fund adaptation actions across its Member States, ensuring that climate change becomes a key consideration for all sectors. The EEA has recently published *Climate change, impacts and vulnerability in Europe 2012* (EEA, 2012). This is a comprehensive report on past and projected climate change and related impacts in Europe, based on a range of indicators. The report also assesses the vulnerability of society, human health and ecosystems in Europe and identifies those regions in Europe most at risk from climate change. The report also discusses the principle sources of uncertainty in the indicators and notes how monitoring and scenario development can improve our understanding of climate change, its impacts and related vulnerabilities. The report can be seen as a snapshot of societal vulnerabilities related to climate change in Europe, and as such provides boundary conditions for the development of adaptation measures.

The European Commission has contributed to regional-scale adaptation by ensuring that European science agendas take account of the need for climate data and information. The objective of the EU's Seventh Framework Programme (FP7) space component[16] is to support a European space policy focusing on applications such as global monitoring for environment and security (GMES, now denoted Copernicus), which has benefits for citizens as well as other space foundation areas for the competitiveness of the European space industry. In particular, the European Commission intends to support the establishment of a Copernicus climate-change service, highlighting priorities including the improvement of Earth System re-analyses to include the hydrological cycle, coupling the ocean and atmosphere and feedback mechanisms. Issues such as data archiving, integration and access to data through a central clearing-house mechanism should be tackled, as well as implementing a gridded approach to impact indicators. Such initiatives show that the European Commission is planning to make a strong contribution to the science framework required in climate adaptation.

5.3 Adaptation to specific risks

Flood-risk reduction

Protect–Accommodate–Retreat

There are three basic adaptation strategies for coping with floods (Kundzewicz and Schellnhuber, 2004):

- protect – as far as technically possible and financially feasible, bearing in mind that absolute protection cannot be achieved;

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[15] csp.iri.columbia.edu

[16] http://cordis.europa.eu/fp7/home_en.html

Table 5.1 Selected web portals dedicated to climate-change adaptation and other climate-change issues

Country	Web portal
Austria	The Austrian Climate Portal http://www.accc.gv.at/englisch/index.htm
Denmark	Climate Change Adaptation (very practical) http://www.klimatilpasning.dk/en-us/Sider/ClimateChangeAdaptation.aspx
Germany	Competence Center for Climate and Adaptation KomPass http://www.anpassung.net Climate Service Center
Netherlands	PCCC Platform Communication on Climate Change – KLIMAATPORTAAL http://www.klimaatportaal.nl/pro1/general/home.asp
Norway	Norwegian Climate Change Adaptation http://www.regjeringen.no/en/dep/md/kampanjer/engelsk-forside-for-klimatilpasning.html?id=539980
Portugal	In a Changing Climate http://www.numclimaemmudanca.pt/en/index.html
Spain	Spanish Climate Change and Clean Energy Strategy http://www.magrama.gob.es/es/cambio-climatico/publicaciones/documentacion/estrategia-espanola-de-lucha-contra-el-cambio-climatico/ pdf version in English: http://www.magrama.gob.es/es/cambio-climatico/publicaciones/documentacion/cle_ene_pla_urg_mea_tcm7-12478.pdf
Sweden	Climate Adaptation Portal http://www.smhi.se/klimatanpassningsportalen
Switzerland	Climate Portal Swiss Climate Change Scenarios http://www.ch2011.ch/ http://www.climate-change.ch
United Kingdom	Climate Portal, giving advices by sector of business or activities http://www.defra.gov.uk/environment/climate/sectors/

- accommodate – living with floods;
- retreat – relocate from flood-risky to flood-safe areas. This is often the last option to rectify maladaptation – the inappropriate management of flood-prone areas – and flawed floodplain development.

Often, the actual strategy consists of a mix of these three components.

Protection

Protection refers to taking technical measures to reduce the likelihood and/or the impact of floods in a specific location, including building defences, or the upgrading of existing defences, such as widening the space between embankments, raising existing embankments around low-lying areas, heightening and strengthening levees, creating more storage space by enlarging reservoirs, arranging polders, and improving drainage systems, particularly urban drainage.

Tried and tested solutions for flood protection are to build dikes along a river thereby raising the water levels that can be accommodated, to cut off bends increasing the water velocity and allowing water to move away from vulnerable areas more rapidly, and to dredge the river reducing water levels by enlarging river capacity.

There have been advances in the use of some of these approaches – for example, the probability of dike failure can be reduced by constructing a super dike so wide that virtually no flood can completely erode it through overtopping or seepage. There can be two dike lines: a lower dike, near the river, to protect against small floods but allowing the land behind to be used for agriculture, and a high dike to protect the rest of the flood plain. Alternatively, the high dike can be close to the river, and the second, lower dike a secondary line of defence. A new version of an old solution aims to change the flood volume by means of side or branch polders as have been developed on the upper Rhine. Such polders can

BOX 5.3 ADAPTATION AT A LOCAL SCALE

In general, regional adaptation strategies appear uncoordinated. Initiatives at the local level, by towns and parishes, for example, are only partially supported by initiatives at regional levels. At the national and the European level initiatives appear not to be particularly harmonised. Below are some examples of European projects.

Climate change impacts in the northwest United Kingdom

A briefing guide for the northwest United Kingdom (Eclipse Research Consultants, 2010) outlines six steps for 11 climate-change impact categories and provides possible responses for buildings, neighbourhoods and cities. For each relevant impact category, possible responses or multi-purpose responses are given. A number of sign-posts have been developed with information about their practical implementation, about UK case studies available and about local examples in the region.

Sweden

Dam safety related to ongoing and future climate change is of great importance in Sweden. The Swedish Flow Committee has developed new guidelines on extreme floods. These have been developed after extensive research on climate-change scenarios in terms of heavy precipitation. Additionally, hydrological models have been adapted and used to calculate scenario floods at the dam site. Parts of Sweden may expect dramatic increases in extreme (100-year) floods. Following these studies, dam safety needs to be examined in view of both today's and future climates (SOU, 2007).

Germany

North Rhine-Westphalia

The North Rhine-Westphalia *Handbook for City Climate* (NWR, 2011) gives check-lists for action and measures for climate-change adaptation to heat stress, extreme precipitation and droughts. Practical advice for urban planners is given in tables, with information on the shadowing or greening of roofs or, in the event of heavy precipitation, construction of retention basins and infiltration areas.

Bavaria and Baden-Württemberg

In Baden-Württemberg and Bavaria, ongoing studies in the framework of the KLIWA (2011) cooperation project have lead to a new set of guidelines for flood-protection measures along rivers (LFU, 2005). These guidelines are based on comprehensive studies of the changes of flood peaks for different recurrence times (probabilities) under future climates. The principle is to calculate the design on the basis of the usual flood protection guidelines, and then to apply the so-called climate-change factor, which depends on the geographical region. This is a very pragmatic and simple way to consider climate change in the design of flood protection measures. The new guidelines are legally binding in Baden-Württemberg and in Bavaria.

reduce peak flows by smoothing out the flood wave by extending its time of action.

Another frequently used solution for protecting large cities is to reduce river discharge by means of parallel flood canals as used on the Danube in Vienna, Austria and the Odra in Wroclaw, Poland.

Typically, dams on main streams are not favourably regarded today, because of the significant effect they have on ecological processes, notably fish migration, but building retention basins on tributaries, often combined in a network of reservoirs and small creeks, is possible. The strategy used in Baden-Württemberg, Germany, for example, is to build many small reservoirs, adequate for local protection against small-design floods (N = 20–50 years), to eliminate narrows in the river's course, and to build dikes where additional protection is needed.
In some parts of Europe, notably in the United Kingdom, river restoration, removing canalisation and restoring meanders and water meadows has proved successful in slowing the movement of floodwater, protecting urban areas downstream[17]. Finally, in order to determine total risk and to prepare against events exceeding the design floods, the residual risk associated with failure of the protection system should be determined.

Accommodation

Accommodation implies being aware of the existing flood risk and trying to reduce susceptibility to flood damage

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[17] http://cdn.environment-agency.gov.uk/geho0310bsfi-e-e.pdf

BOX 5.4 NATIONAL ADAPTATION STRATEGY IN PORTUGAL FOR DIFFERENT SECTORS

In 2009 the Portuguese Government published the National Climate Change Adaptation Strategy. The objective is to adapt the country to the impacts of climate change in different socio-economic sectors, such as water resources, biodiversity, human health, energy, tourism, agriculture, fisheries, security and coastal zones. For each sector a public institute from the central administration has been nominated to coordinate the development of the adaptation strategy for its sector. The implementation of the adaptation strategy is still at the very beginning.

Adaptation to extreme weather events in the coastal zones of Portugal

As regards extreme events in the coastal zones of Portugal, storm surges could reach 1 m, especially in the northern part of the northwest coast in association with the approach of extensive and deep low-pressure systems (SIAM II, 2006). The most relevant impacts are expected to result from a change in wave climate characterised by a clockwise rotation of 5–15° of the resultant vector describing the yearly wave-power density (SIAM, 2002; SIAM II, 2006; Andrade *et al.*, 2007). This rotation is very likely to significantly increase erosion of the west coast, particularly from the Douro estuary to Nazaré.

Adaptation measures to protect erosion-exposed coastal land has been recommended for 24 % of the coastal length and encompasses port upgrading, construction of seawalls and groynes, together with combined solutions of soft and hard protection, including beach nourishment (SIAM II, 2006). Retreat and relocation is recommended for 4.3 % of the coast. However the decision-making process by local and central administrations regarding adaptation to the risk of erosion and inundation in coastal zones has been very slow and unable to deal efficiently with the long-term aspects of the problem. Most action is reactive and deals with immediate threats and damage.

Tourism and climate change

Portugal is an important tourist destination in Europe, mainly due to its diversified landscape, cultural heritage and mild climate, and tourism is a significant source of revenue. The impact of climate change was studied in a project that focused on the effects of climate change on air and water thermal comfort and its implications for tourist demand factors, tourists and local population health and energy-supply demands (CLITOP, 2007). Four tourist destinations were studied: Algarve, Lisbon, Oporto and Madeira Island.

and the impacts of flooding by a mix of technical and non-technical solutions. In Europe, the importance of not relying only on technical flood-protection measures has become increasingly acknowledged. Land-use planning measures are usually regarded as effective, particularly where they serve the interests of both flood management and nature protection. One of the options is watershed management, keeping water where it falls, to reduce surface runoff and erosion. Restoration of wetlands and floodplain forests and reconnection of old river branches are being considered to aid retention of water in the landscape. There is a call, for example in Germany, the United Kingdom and the Netherlands, to give more space to the rivers, to designate areas that may receive flood waters and to devise floodplain protection measures. Planning regulations are being implemented or proposed, which restrict the development of new settlements in floodplains. Such land-use planning measures are usually regarded as effective both for flood-water storage and for nature protection. In some countries, highway embankments are planned to serve as emergency levees.

Planning regulations may impose conditions on the design of structures and on the use of materials and equipment that are a threat to water quality – for example, oil-fired heating systems.

The most effective non-technical means of flood protection is to make sure that fatalities are prevented and that goods and buildings are protected and insured. Lives are saved in Europe, because of effective early warning and response systems.

Such systems include the collection of observational data, their processing to produce forecasts, the dissemination of warnings and the communication of response strategies. Hydro-meteorological observations provide the basic information which is then employed

The impacts of more frequent forest fires driven by climate change and of thermal extremes on human health, using epidemiological methods, were assessed. The main conclusion from these is that significant seasonal shifts in tourism fluxes are expected in the future, depending on the origins of the tourists. Climate model simulations indicate greater impact of heat waves and ozone concentrations on mortality until the end of the 21st century (Almeida *et al.*, 2010; Garrett *et al.*, 2012).

Sintra, near Lisbon, a UNESCO World Heritage site, is of great touristic value. Its municipality was the first in Portugal to conduct, at a local scale, a vulnerability, impacts and adaptation (VIA) climate-change multi-sector assessment and to develop a municipal climate-change adaptation and mitigation plan (PECSAC, 2009). This assessment is based on an integrated approach for adaptation to climate change, by considering other strategic sustainable development plans, such as the National Strategy for Sustainable Development, the Environment Plan for the Municipality and the Sintra Energy Plan. The sectors considered were partly the same as in the SIAM I and II projects, plus the tourism sector due to its great relevance for the municipality.

Cascais, near Sintra, published a municipal strategic plan for adaptation to climate change (PECAC, 2010), which was developed following a similar methodology and choice of sectors to Sintra's. One of the outcomes of this project is the implementation of a local green structure where small streams are being cleaned and rehabilitated to reduce flood risk (Agência Cascais Natura, 2010). Moreover a special contingency plan for heat waves in the Cascais Municipality, involving health centres, hospitals and the civil protection municipal services was also developed (Casimiro *et al.*, 2010), as was the impact of climate change on some specific tourist activities such as golf (PECAC, 2010). The project benefited from the active involvement of public and private stakeholders.

The number of extreme weather and climate events, in particular floods and droughts, is very likely to increase. These events, together with the increase in average temperature, will change water quality and availability in the central region of the country.

in well-tested models to forecast river flows. Warnings on the extent, severity and timing of a flood event are issued and disseminated, early enough, to the appropriate authorities and to the public, particularly those in the path of the water. Finally, it has to be ensured that the affected people are able – and willing – to respond to the warning, by developing clear warning and risk communication systems.

A forecast-warning-response system is a part of a broader flood-preparedness system that includes other activities, ranging from planning the emergency rescue of victims to moving valuable property from areas likely to be flooded. It also includes the ability to undertake post-flood responses such as relief for the immediate needs of those affected by the disaster; reconstruction of damaged buildings, parts of the infrastructure and flood defences; and recovery and regeneration of the environment together with economic activities in the flooded areas. As a follow-up, a review of the flood management activities is valuable in order to improve the process and assist planning for future events.

In brief, the term flood-preparedness system also encompasses all tasks that are necessary for ensuring that administrators, utilities and people do know what to do and have the necessary supplies. The competence of the institutions involved and the chain of command for managing the flood disaster must be clear.

Preparedness measures are important under 'protect' and 'accommodate' strategies. Emergency measures must be put in place to protect levees from breaching and over-topping. Decisions on the operation of reservoirs and polders have to be made.

Object protection is a simple strategy, effective for flooding levels that are not too high. People can build walls around their properties, water-proof low parts of their houses or raise the thresholds of the doors: in many regions, living quarters are half a storey above ground, with the basement used for goods that can be flooded, while valuables that can be damaged are kept on higher levels of the houses. In some areas, people protect themselves from frequent flooding by building their houses on stilts, so that the floor of the living area is above flood level.

Insurance reduces material losses due to flooding. Householders can insure against damage to their property and possessions, provided that insurance companies are willing to provide cover. Commercial organisations can also insure against physical damage but, in addition, they can insure against loss of profits resulting from a flood event. In Europe, there is a range of different mechanisms of insurance provision. In some countries insurance is provided by commercial companies and can be purchased by householders as an additional risk added to their usual household policies, or flood cover is automatically included in standard household insurance policies. Most commercial organisations, particularly large multi-national companies, will have their own private insurance in place to cover flooding in addition to any provisions by the state. However, in many countries, the government provides emergency relief if a flood is catastrophic.

Retreat

Retreat, relocation of a population and their possessions, is a simple, and in some cases, cost-effective way to keep people out of harm's way. Permanent relocation of people living on flood-prone land has been recommended, and in some cases implemented. This should be on the basis of either adequate financial compensation or by offering replacement housing in flood-safe areas.

More common is temporary relocation, through evacuation, as part of the flood preparedness system. In response to a flood warning, people are moved out of the dangerous region, only returning when it is safe to do so.

Perception and awareness of flood risk and flood-risk change

Changes in flood risk occur only gradually, and are usually imperceptible to laymen. Occurrence of a major flood disaster creates awareness of the flood danger and gives rise to a demand for protective action. Lack of awareness of the flood risk is a common problem in developing and developed countries alike.

There is common but unjustified confidence among laymen in the absolute security provided by structural defences. These defences are designed to withstand specific forces and may not withstand a flood greater than the design value. Furthermore, change is a complicating factor. The existing infrastructure may not guarantee an adequate level of protection against future floods and may need to be thoroughly adjusted (Milly *et al.*, 2008). Without that, systems will be over- or under-designed and will either not serve their purpose adequately or be overly expensive. However, no precise and quantitative scientific information can yet be provided to support changes in design.

Therefore, for practical purposes, risks are calculated based on existing land use, with the help of a growth factor. The main purpose of risk calculations is twofold: for design, it is used to compare the risks of different designs; for priority setting, it is used to determine where the cost–effect ratio will be lowest to optimise the use of available financial resources. In practice, however, the degree of protection and the way it is accomplished are set by the availability of funds and political will.

Short-term memory, also known as a hydro-illogical cycle, is a widespread and serious problem that hampers preparedness. During a flood-free interval, decision makers gradually become uninterested in the funding of improvements in flood-protection systems, and citizens become increasingly less risk-aware. Structural measures, such as levees, dams and storage reservoirs, are expensive and it takes a long time from the initial plan to the completion of the construction. This time scale is not compatible with a time horizon for planning driven by the election-cycles of democratic countries.

In contrast, if extreme floods occur at short time-intervals, awareness may remain. For example, two successive floods with similar peak flows occurred in the Rhine basin in Germany, in December 1993 and January 1995, just 13 months apart. The damage caused by the second flood was much smaller than that by the first. When the second flood came, memory of the first disaster was still alive, so people were much better prepared.

Policy responses in Europe and criteria for flood defence design

In reaction to the recent flood disasters in Europe since the 1990s, especially the summer 2002 floods, and the pressure of more risk-averse and risk-aware populations, a new perspective on flood risk has evolved. People demand protection and politicians are taking notice. At government level, legislative action has been taken to reduce risks and build a uniform approach to the management of floods. The European Union's Floods Directive (CEC, 2007), applying to inland coastal waters across the whole of the EU, is expected to aid reduction and management of the risks that floods pose to human life and health, the environment, cultural heritage, economic activity and infrastructure. The directive required EU Member States to carry out a preliminary assessment to identify the river basins and coastal areas at risk of flooding by 2011. For such zones, hazard maps have to be drawn up by 2013, and flood-risk management plans focusing on prevention, protection and preparedness have to be designed by 2015. Flood-hazard and flood-risk mapping will aid in developing protective measures and indicate, quantitatively, the danger to people living in unsafe areas and to insurers. Assessment is expected to provide a rational choice basis for allowing development at a particular site, taking into consideration how the development may affect flooding. The implementation of the Floods Directive requires adjusting national rules and regulations, but how to adjust to changes in extreme floods is left to the Member States.

Flood-risk management, required in the Directive, is now a well-defined procedure. As noted by Plate (2002), it takes place on three different levels of action: the operational level, which is associated with maintaining the existing system; the project-planning level, when a new project, or the revision of an existing one, is considered; and the project-design level, which is embedded in the second level and describes the process of reaching an optimal solution for the defined goals. A central part of flood-risk management is the planning phase, with its emphasis on risk assessment and project design and implementation. For flood-risk assessment, the changes of both load and vulnerability have to be considered.

In Switzerland, flood protection approaches must now, by law, seek solutions that can be adapted flexibly to future requirements: existing flood-control structures must be reviewed regularly as to their protective effect, and adapted as appropriate. The overload danger of a flood-control structure must also be examined. Responses prepared in advance for such a case, such as targeted spillage in areas with a lower hazard potential, can then prevent additional damage. Hazard mapping, too, is mandatory for all regions and must be transposed into spatial planning. This means, for instance, providing enough space for peak discharge runoff, prohibiting construction in highly endangered areas, etc.

Because of the wide range of possible outcomes within available future climate projections, precisely which procedure should be used for redefining design floods for the specification of flood defence design, for example a 100-year flood, remains open. For the time being, adjusting design floods using a climate-change factor is recommended. There is continual progress in model development and the understanding of climate change and its impacts, which means that flood-risk reduction strategies should be reviewed on a regular basis, in the light of new data and information, and – as necessary – updated.

In Germany, for example in Bavaria and Baden-Württemberg, flood design values have been increased by a safety margin, reflecting the results of climate-model calculations based on several climate-change scenarios. The projections for 2050 include an increase of 40–50 % in small and medium flood discharges and of around 15 % in 100-year floods. In the United Kingdom, the precautionary allowance includes the projection of an increase in peak rainfall intensity of up to 20 % by 2085, and in peak river-flow volume of up to 20 % by 2085 (DEFRA, 2006), based on early climate-change impact assessments. A climate-change factor is being taken into account in any new plans for flood control measures in the Netherlands (EEA, 2007). Measures to cope with the increase in the design discharge for the Rhine in the Netherlands from 15 000 to 16 000 m^3/s must be implemented by 2015, and it is even planned to accommodate a design discharge of 18 000 m^3/s in the longer term because of climate change. In areas where 100-year floods are expected to become more frequent, the existing defences will simply provide a higher-than-standard protection level, assuming that all other flood protection measures remain.

Drought management and adaptation

Traditionally drought management has been reactive, relying largely on crisis management but this approach has been ineffective because response is untimely, poorly coordinated and poorly targeted to drought stricken groups or areas (Wilhite, 2005; Field *et al.*, 2012). The IPCC 2011 *Summary for Policy Makers* (Field *et al.*, 2012) recommends a set of options for drought-risk management and good practices for adaptation to droughts in West Africa. In the following sections we present a selection of these options that are valid for Europe. Most importantly there is a need for sophisticated and reliable drought monitoring tools and early-warning systems that integrate seasonal forecasts with drought projections with improved communication involving extension services.

Furthermore, the following low-regrets options that reduce exposure and vulnerability across a range of hazard trends are recommended:

- water demand management and improved irrigation efficiency measures;
- conservation agriculture, crop rotation, and livelihood diversification;
- increasing use of drought-resistant crop varieties;
- risk pooling at the regional or national level.

5.4 Sector-focused adaptation strategies

Health

Extreme weather has a range of impacts on human health, requiring a number of specific adaptation strategies.

Where extreme weather affects the patterns of disease, through the transport of vectors, for example, or by providing, even if temporarily, conditions conducive to the viability or transmission of infectious diseases, the key adaptation strategy is a combination of information for health authorities and the availability of suitable vaccines or medicines. Planning for early warning and treatment is essential, in particular where future patterns of extreme weather may introduce hitherto unknown or rare health threats from disease.

Heat waves have become an increasingly visible factor in health in recent years and health authorities through Europe have considered measures to improve identification and emergency care for vulnerable parts of populations, notably the old and the very young. In addition to improvement of the management of incidents, there are strategic options for reducing the hazard from extreme heat, focusing on improving the indoor climate through the use of building codes.

Transport

The key adaptation strategy for transport systems is improvement of design standards and information systems for road and rail links. This is expected to include:

- specification of road surfaces and drains to allow for more intense precipitation;
- larger trackside drains for railways;
- modified road surfaces and railway track design to accommodate higher temperatures;
- improved early-warning systems for road and rail users.

For air transport, the main adaptation option is improvement of information systems for airline operators and passengers. For airport operators, improvement of the winter resilience of runways and other infrastructure, learning from parts of Europe with a history of cold extremes, strengthened early-warning systems and improved incident management systems at airports will be required.

For the marine sector, where storms are a major hazard for infrastructure and vessels, a review of harbour design standards will be required in the light of evidence of changes in patterns of storminess in Europe.

Energy

Design standards for transmission systems will require review and, in some cases, it may prove desirable to consider relocating lines or other key infrastructure underground to improve storm resilience.

Water supply

Strategies for improving resilience of public water supplies include:

- improved water storage in response to expectations of longer periods of drought;
- reduced losses from distribution systems;
- flood defence for water treatment plants;
- strengthening emergency preparedness and public information systems.

5.5 Adaptation: an international perspective

The recent IPCC SREX report on extreme weather (IPCC, 2012) provides an up-to-date and comprehensive discussion on climate-change adaptation. This is also expressed as climate-proofing, which may apply to both existing and new infrastructure, and may for instance include upgrading of ports to account for future sea-level rise and changes in the frequency and size of storm surges. Climate proofing can also include investment in education, ensuring that the impacts of extreme weather and action to counter them become better known. The global estimated cost of climate-proofing with a 2030 time horizon could be in the range US$ 48–171 billion per year (SREX; global estimates in 2005 US$), but these figures are quite uncertain, and the inclusion of such elements and sectors as ecosystem services, energy, manufacturing, retailing and tourism could add further costs.

There are also few analyses on the cost of local risk management, and hence little is actually known about the cost-benefit of these sectors. There have been crude catastrophe risk assessments for calculating the direct cost of storm surges and sea-level rise for Copenhagen, where climatic indicators have been coupled with an economic model. Copenhagen, it was concluded, is well protected and not particularly vulnerable, but assessment of direct and indirect impacts, including disrupted production, job losses and reconstruction time, would, in the absence of protection, be in the range of € 3–4 billion assuming 25 cm sea-level rise and almost € 8 billion assuming a 100 cm rise (Hallegatte *et al.*, 2011). The SREX report provides an overview of different management strategies, including community-based adaptation (CBA) and risk-sharing and transfer at the local level. Reliable information about climate change, however, plays a role for many of these measures.

Chapter 5 of SREX provides some general principles in terms of adaptation and risk management, stressing the point that local participation and the character of the social fabric are important factors for successful outcomes. However, it provides no simple recipe for Europe in terms of specific action, and it is not always clear from the SREX exactly what is needed in terms of local climate information for the underlying analysis of local climate-change adaptation in Europe.

Chapter 5 of the SREX report, however, does highlight a number of specific issues that are relevant to climate-change adaptation. Structural measures that can provide some protection from extreme climatic events may also create a false sense of safety. Sustainable land management is described as an effective disaster risk-reduction tool, but SREX notes that local political and cultural issues must also be addressed, as these are fundamental for developing effective strategies. Furthermore, arriving at a balanced portfolio of approaches may be a challenge for local adaptation to climate extremes, and a one-size-fits-all strategy will have limitations.

The role of climate variability, both natural and emerging new patterns due to climate change, must be addressed in disaster risk management, both for local responses and long-term adaptation to climate extremes. The SREX report observes that this may entail a modification and expansion of local disaster risk-management principles and experience. Such risk management includes immediate response and relief associated with disasters in addition to long-term planning, although response planning is part of long-term risk management. In this sense, the implicit role of climate sciences is to provide information about the range of plausible scenarios and likelihoods that should be taken into account. In some circumstances, the SREX report suggests that shelter-in-place, or on higher ground in the case of flooding, may offer a solution when there is little time to act. For example, where planning for disasters is a way of life, as it is in Cuba for hurricanes, people are taught from an early age to mobilise quickly when disaster is imminent, and the low loss of life suggests that such measures can be regarded as successful. Another response involves the monitoring and surveillance of diseases whose risk may be altered by more extreme events including flooding and heat waves.

Structural measures considered in the SREX report include means to minimise damage associated with floods, droughts, coastal erosion and heat waves, which, it is noted, often involve engineering work. It is crucial that such measures are well designed and that they do not fail due to misjudged design or lack of maintenance. Furthermore, adapted insurance policies can provide incentives for local governments to implement sensible area planning and building codes.

The SREX also notes that social networks can play a role in influencing people's perception of and response to risk, and opinion leaders can also play a role in promoting practices and influencing how society adapts and responds to natural hazards. Communities with stronger social networks may be better prepared to deal with extreme climatic events because they have better access to information, coordination, and mutual support.

Climate-change adaptation involves different levels of governance and the role of local governments is particularly important. An example from the United Kingdom is the Greater London Authority (2008), which has prepared a public consultation draft of its adaptation strategy to climate change, highlighting actions required to deal with changing risks associated with flooding, droughts and heat waves. The SREX report identifies the local government network, the International Council for Local Environmental Initiatives (ICLEI)[18] as a useful resource for information. In some cases, such as Rotterdam, adaptation to climate change has also been seen as an opportunity for wider transformation, although much action in practice focuses narrowly on risk reduction and protection for infrastructure and citizens.

SREX stresses the importance of risk communication, but notes that formal efforts to provide information about hazards and hazard adjustments alone may not always suffice. In the SREX report it is suggested that presentation of phenomenon, risks, impacts and adaptation actions through graphics, especially, would be a major aid to climate 'literacy'.

The vision set out in the European Joint Programming Initiative 'Climate'[19] (JPI-Climate) strategic research agenda highlights the need to transform energy systems to reduce dependence on fossil fuels and the need to protect European citizens, business and nature from climate risk. Although mitigation action is not directly linked to adaptation, it is recognised that the degree and cost of adaptation required and the severity of future climate impacts are dependent on the future levels of greenhouse gases (Solomon *et al.*, 2007).

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[18] http://www.iclei.org

[19] http://www.jpi-climate.eu

CHAPTER 6 EXAMPLES OF A SECTORAL APPROACH TO ADAPTATION TO WEATHER: AGRICULTURE AND FOOD SECURITY

6.1 Adaptation to extreme events in agriculture

Introduction

Global climate change has a fundamental influence on natural and artificial ecosystems, affecting the quantity and quality of crops, and thus the profitability of agriculture. The weather extremes occurring most frequently in Europe and thus having the greatest influence on agriculture are low or high temperatures and a lack or excess of water (Faragó *et al.*, 2010). The knowledge available on agricultural effects is based on a wide range of sources of information derived through assessment of different kinds:

Assessment of expected unfavourable effects include:

- detailed analysis of years with extreme weather events in recent decades and of the correlation between climate data and the yields of major agricultural crops in various regions of Europe (data collection and processing);
- compilation of the results of model experiments performed under controlled conditions;
- determination of the extent to which extreme weather events reduce yield quantity and quality, based on measured and predicted data.

The focus in this chapter remains firmly on the unfavourable impacts of climate change on agriculture because the emphasis is on extreme events, and weather extremes rarely result in favourable outcomes. Although in some cases global warming can be favourable for agriculture, for example by lengthening growing seasons or through the impacts of higher levels of carbon dioxide on yields, impacts of extremes of heat, precipitation or wind are invariably negative. Changes over the long term in average growing seasons may enable the growing of crops in more places or extend the range of crops that can be cultivated, but may also increase the sensitivity of crops to pests and disease, weakening them and making the effects of extreme weather more severe. Farmers have reached a kind of accommodation with the current vicissitudes of the climates in which they work, but will find the exacerbation of extremes brought about by climate change highly challenging. For this reason this chapter considers changes in extreme weather in the context of general long-term trends as climate responds to global warming. Important historic extreme events are summarised in Appendix I.

Impacts of extreme weather on agriculture

Agriculture, in common with natural vegetation, is sensitive to weather variability and climate change. It is expected for example that average temperature increases will be likely to hasten the maturation of annual crop plants, and that this will reduce their total yield potential. In addition, very high temperatures may cause severe losses through a range of mechanisms (see Appendix II).

However, it is possible that the net result of warming may in some cases provide higher yields, although that may cause disruption to food supplies through marketing and logistics problems. Climate-change projections include an increased likelihood of both floods and droughts, which both tend to reduce production. The variability in precipitation, in terms of time, space and intensity, will make EU agriculture increasingly unstable and make it more difficult for farmers to plan what crops to plant and when (Veisz, 2011).

In the majority of EU countries, the key question for field crop production will be the collection and preservation of rainfall. This will require tillage techniques able to cope with both drought and excessive rainfall, together with expansion of irrigation facilities (Birkás *et al.*, 2009). The use of technologies adapted to local conditions and crop requirements will be especially important for field crop production in the future, together with the breeding and introduction of varieties with better tolerance of drought and extreme weather events, the use of varieties capable of adapting to local conditions, changes in the crop production structure and promotion of more suitable crop sequences.

As a result of plant breeding, genotypes are now available with better stress-tolerance – to drought, frost and heat – making them capable of producing significantly higher yields than other varieties even under weather conditions differing greatly from the norm (Bencze *et al.*, 2010; Varga *et al.*, 2010). Nonetheless, continued breeding efforts are required and if breeders are to be capable of meeting this challenge, they must be backed up by extensive basic research, investigations on abiotic stress effects and technical improvements (Veisz *et al.*, 2008; Balla *et al.*, 2011; Bencze *et al.*, 2011; Varga *et al.*, 2011). Wide-ranging cooperation on a European and international scale is essential in plant breeding, as in other fields.

Experience shows that, as a result of climate-change pathogens, pests and weeds new to a given region will appear. Due to their aggressiveness and mass occurrence, this will be a challenge for plant protection experts. There will be a considerably greater need for expert knowledge, predictions, advisory services, integrated plant protection, up-to-date equipment and reserve chemicals.

However, greater use of agricultural chemicals can affect long-term health and pose environmental and economic risks, so the aim will be to expand the use of high-precision techniques, which use smaller quantities of chemicals in the defence against diseases, pests and weeds, and to promote the exploitation of biological control measures. Unfortunately, both pest damage and pesticide use have increased in recent years.

The occurrence of pests and disease is often associated with extreme weather events or weather anomalies such as early or late rains and lower or higher than usual humidity, which in themselves are capable of altering agricultural output (Bencze *et al.*, 2008). Recent climate trends, such as higher night and winter temperatures, may also contribute to a greater prevalence of crop pests. Higher temperatures reduce the winter kill-off of insects and lead to increased rates of development, with shorter times between generations. Wet vegetation promotes the germination of spores and the proliferation of bacteria and fungi. Prolonged droughts, on the other hand, whilst a threat to some pests and diseases, may encourage other and more novel pests and diseases, especially those carried by insects.

In the field of agricultural mechanisation, responses to the challenges raised by extreme weather are expected to differ greatly from one region to another: the use of farm machinery in a changed climate may, for example, result in the greater soil compaction and disturbance, with consequent loss of soil function. There are, however, a number of solutions that can be generally applied:

- technological changes – development and introduction of techniques to improve the water regime;
- combining or omitting tillage operations – to prevent or reduce the development of unfavourable soil status;
- the purchase of faster, more flexible, more efficient machinery – for the better exploitation of the optimum time for various operations;
- emergency equipment – purchase of special machinery, such a pumps, only needed in emergencies.

Effective control of the impacts of farm machinery will require more investment but less efficient exploitation of machinery, so that the negative effects of weather extremes can only be counteracted at increased cost. Improvements in agricultural logistics, however, are justified not only because of yield fluctuations and possible declines in yield, but also by the need to create crop reserves and store them safely.

Because they have complex impacts, regional projects for the establishment of multi-purpose water reservoirs, for irrigation, fish farming, water storage, groundwater-level manipulation, flood control, natural habitats, angling, recreation, and the like, will require careful planning in order to make the best use of possible locations (Anda and Varga, 2010).

Fruit growers have been fighting the effects of extreme weather events for hundreds of years. Rising temperatures, increasing aridity and more frequent bad weather events increase the risks as yield quality and reliability deteriorate (Makra *et al.*, 2009; Mira de Orduña, 2010). An increase of about 50 % in the frequency of frost and hail damage is expected in Central Europe. Timing of these extreme events is crucial; although, for example, the winter of 2011 was very mild as a whole, frost damage in apricot, cherry and walnut plantations in Central Europe was around 80 %.

The choice of growing sites will be increasingly important in overcoming the effects of climate change, together with the use of varieties with satisfactory eco-tolerance and resistance, plant protection, irrigation, hail prevention using rockets and nets, and cultivation methods, including the choice of row and plant distances and the crown shape. As in the case of maize production, the zonal limit for vine production and wine-making is likely to shift northwards, while negative climatic effects such as frost, withering and rotting may also be experienced, together with a reduction in the life-span of the vines and a deterioration in the quality and quantity of the wine. Meteorological and plant-protection predictions will be important in avoiding these problems.

The yield averages of heat-loving vegetables species such as peppers, tomato, cucumber, water melon and maize may increase more in response to intensive technologies than those of cold-tolerant species, so it would be advisable to concentrate on producing the former group. Cold-tolerant species such as peas and brassicas could be produced in Central and East Europe in early spring, when the mean temperatures are favourable for their development. The use of forcing equipment, particularly cheap polythene greenhouses, should be increased so that heat-requiring species grown for fresh consumption can be produced more reliably and better timed to meet market demands.

Due to the danger of unfavourable weather – heat, chills, temperature fluctuations, rainfall deficit or excess, hail, strong winds, etc. – essential factors in vegetable production are a wise choice of growing sites; irrigation (drip and trickle, to water, refresh or humidify crops; frost protection); shading; covering; drainage; use of hardy, well-developed seedlings; and protection against strong winds.

Climate change may also have a damaging effect on the collection and production of medicinal and aromatic plants. Some 180–200 such plants are collected or produced in Central Europe. Climate change is likely to have the greatest effect on collected species, since those that are grown are heat demanding and their growing conditions can be adjusted to some extent. Species respond differently to changes, in terms of both biomass and the quantity of valuable components. The latter is likely to decline, though in some cases, however greater accumulation may occur.

Climate change will also have a great influence on intensive livestock farming (Miraglia *et al.*, 2009) although different animal species and husbandry technologies respond differently to environmental pressures. In Central Europe the increasing frequency of very hot days and droughts may weaken livestock, reduce the yield and quality of fodder crops and grassland, and highlight deficiencies in buildings, technologies and feeding. Throughout the EU there have been fierce debates on the direction and magnitude of livestock farming.

Intensive livestock management results in enhanced sensitivity, so that the animals tend to respond to the slightest shock with an immediate drop in performance. The breeds used in free-range farming are more adaptable, due both to their genetic make-up and the techniques of husbandry. In addition to performance and quality, breeders should consider the tolerance of animal breeds to climate change and to proactive improvements in housing conditions. Another effect of climate change on free-range or near-natural livestock farming could be that the composition of natural swards – grassland or pasture – will shift in favour of drought-tolerant species, the nutrient content of which may differ from that of the present pasture species.

Despite the drop in specific yields and a possible deterioration in fodder quality, the tendency for the weather to become hotter and drier will have a less severe effect on livestock farming based on cereals, as is the case under the climatic conditions of Central Europe, than in countries where the livestock is fed on hay and fresh fodder. Due to the decline in the stocks of grain-fed animals, grain surpluses may even accumulate when the weather is good, leading to marketing, transportation and storage problems. There are several potential solutions: the construction of sufficient, high-quality storage capacity, a search for new markets, utilisation as bioenergy, or an increase in stocking numbers in order to turn the grain into meat or animal products.

To protect the atmosphere and reduce environmental pollution, great importance will be attached to minimising emissions of greenhouse gases from livestock farms. A solution must also be found for the containment and utilisation of liquid manure, which has caused numerous problems recently. The establishment of biogas plants would provide an alternative source of energy, while also protecting the atmosphere and recycling nutrients.

6.2 Impacts on natural ecosystems and forests

In the recent past, severe weather events have caused damage to the natural environment. For example, frost and wind storms have resulted in adverse impacts on forest stands, though the natural regeneration ability and resilience of the ecosystem have mostly rehabilitated the forests. The primary limiting factor facing forest management as the result of climate change is likely to be rainfall, which, together with the landscape form – flat or hilly and mountainous land – and other features, is already a decisive factor in determining forest limits (Maracchi *et al.*, 2005; Mátyás, 2010). Changes in the quantity and distribution of rainfall are likely to result in a shift in the boundary between forest steppe and deciduous forests, and a substantial alteration in species composition within forest areas is also predicted. Forestry is one of the sectors most endangered by climate modifications, due to the difficulty in its ability to adapt to rapid change (Lindner *et al.*, 2010). Although tree species are capable of migrating 25–40 km over a period of 100 years, a 2–3° C rise in temperature may shift climate zones by several hundred kilometres over the same period (Jouzel, 2007). In mountain ecosystems, a shift to increased temperature will favour the invasion of low-latitude species at higher altitudes where that will compete with the cold-adapted species of the upper mountain levels. Biodiversity can thus be expected to decrease, possibly resulting in ecological disasters in some regions. Rising temperatures also favour the spread of invasive pests, which could lead to the rapid destruction of large areas of forest. As the result of drought and high temperatures, forest fires also could become more frequent. As a consequence of this disruption to the ecological equilibrium, the carbon dioxide balance of forests is likely to shift towards production, thus aggravating climate change in the long term.

Wind storms cause considerable damage to Europe's forests. The Great October Storm of the night of 15/16 October 1987, with winds gusting to 150 kph, caused major loss of trees in the south of England. The millennium storm of 2 000 caused massive damage to forests in France.

The combination of long-term change with warmer mean temperatures and greater extremes including heat spells, droughts and floods could have negative impacts on agricultural production throughout the EU, increasing vulnerability, reducing productivity and leading to significant economic losses. The more frequent occurrence of floods, water-logging, sudden downpours, strong winds and violent storms will not only affect plants and animals directly, but also indirectly through effects on the soil.

Even the best agro-ecological regions of Europe may be affected by water deficits. Droughts are likely to strike some parts of Europe, especially in central and southern regions, in 20–50 % of years. Over the past 15 years, droughts have been responsible for more than 40 % of the losses caused by extreme weather events. If drought damage is to be mitigated, it is essential to improve the use of existing irrigation capacity and to expand the number of areas that can be irrigated.

In addition to flood damage itself, over the past 20 years there have been several incidences of water surpluses being followed by long periods of drought, making problems involving the water regime one of the major risks for farmers – at present almost 20 % of insurance claims from agriculture are lodged to cover flood damage. Agricultural practice can also have an impact on flooding where it encroaches on river banks, removing natural vegetation that acted as a flood protection. Erosion damage caused by rainwater has been recorded on almost half the farmland in the region. Potentially, all the land area may be subject to wind damage, which can result in mechanical injuries, drifting of the humus layer, the burial of crops and the re-deposition of fine particles. Plants damaged by strong winds are also more susceptible to attacks by pests and pathogens.

Unfavourable effects of extreme weather events on agriculture are summarised for the different European regions in the appendix.

6.3 Factors that could improve crop safety, and appropriate measures

Factors that improve crop safety

To protect crops against extremes, a general improvement in resilience would be desirable through, for example:

- development of soil-protecting farming systems and water-saving technologies;
- breeding and cultivation of plant varieties capable of adapting to changing conditions;
- development of new technologies to exploit the relative advantages of climate change;
- development of a satisfactory IT background and insurance system for farmers.

Measures proposed to achieve these aims

In order to achieve higher resilience, a range of measures will be needed, including:

- risk analysis for the agricultural sector at the regional level. Joint assessment of how economical and efficient adaptation techniques are, in order to set priorities;
- acceleration of plant and animal breeding to improve the available choice. Adaptation studies to select technologies capable of moderating losses due to heat, frost, drought, and new plant pathogens, weeds and pests;
- development and introduction of new technologies leading to multi-purpose adaptation – precision crop-protection and nutrient replenishment, water-saving irrigation, cultivation methods reducing the risks of flooding and drought, protection against hail-induced damage;
- construction of up-to-date irrigation, servicing and IT systems for the prevention of drought damage. Attempts to retain water and ensure continuous plant cover in the worst-affected regions;
- restructuring of the agricultural insurance system to cover rising risks;
- improvements in the infrastructure of agriculture – mechanisation of field crop production, expansion of crop storage facilities;
- larger reserves of food raw materials and foodstuffs;
- education of farmers in the use of new adaptation techniques.

Appendix III summarises measures that can be implemented to moderate the impacts of specific weather phenomena.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The current state of climate science is sufficient to make reasonably robust predictions about some major aspects of future climate change. It gives information about some of the underlying processes that drive extreme weather, for example the conditions that give rise to extreme convective events such as summer storms.

Using the available information from climate models and an analysis of data about extreme weather over the past few decades, it is possible to see some recent trends in extremes and suggest how these will develop in future.

For some, but not all, extreme weather phenomena, it seems that the recent trend has been towards more active and frequent events. Moreover, even where the evidence of trends in the physical impacts of extreme weather is ambiguous, as for example for river flooding, there is still evidence of a trend towards higher losses, suggesting that vulnerability has increased, in this instance through building on more flood-prone areas. Some specific trends and future patterns are as follows:

Wind storms: there is some evidence that synoptic winter storms over Northwestern Europe have increased over the past 60 years, with a maximum of activity in the 1990s. However, controversy remains about longer-term changes since the middle of the 19th century, as results seem to depend on the data-set used. Assuming no adaptation to climate change, simulations of future climate suggest an increase in damage in Northern and Central Europe, of 30–100 % in Central Europe. In Southern Europe, it is expected that there will be fewer storms of this kind.

The data available for convective summer storms are not sufficiently harmonised at present to provide a reliable assessment of recent trends. However, analysis suggests that in future there will be more occasions when conditions are favourable for the development of convective storms.

Floods: the future magnitude and frequency of floods are very uncertain, partly because information about the evolution of underlying causes is uncertain but also because of other confounding factors, including the effects of human intervention.

Damage from floods has increased in the past, but evidence linking this to changes in physical conditions is weak, partly because of a lack of data and partly because of the role of past flood-risk management. It seems that there has been a measure of adaptation but that vulnerability has increased economic losses because there is now more and higher value stock at risk.

Temperature extremes: observations show a trend since the mid 20th century of more hot days, warm days and heat waves, and fewer cold days over most parts of Europe. Most places in Europe will very probably experience more hot and fewer cold extremes as global temperatures increase. The magnitude of hot extremes is expected to increase and of cold ones to decrease faster than mean temperatures over large parts of Europe. The probability of the occurrence of heat waves such as in 2003 in Europe or in 2010 in Russia is expected to increase substantially – for example a 1 in 50-year event may become 1 in 5-year event by the end of the 21st century.

Droughts and dry spells: as droughts and prolonged dry spells are relatively rare events, which exhibit a large natural variability in frequency and intensity, for a potential trend to be detected a large set of observations taken over a long time period are needed. Analysis of the available data suggests that, although increasing summer dryness has been observed in Central and Southern Europe since the 1950s, no consistent trends can be seen over the rest of Europe. In the future, summer dryness is expected to increase further during the 21st century in Central and Southern Europe and in the Mediterranean, leading to an enhanced risk of drought, longer dry spells and larger soil moisture deficits. No major changes in dryness are expected in Northern Europe before the end of the 21st century.

Given these expected changes, investment in adaptation will be required; in particular, in the health sector to address the expected increase in heat waves, in agriculture to address a trend towards more frequent and intense droughts and storms, in forestry to address the increasing risk of forest fires, and in critical infrastructure to address increases in storm frequency and severity.

An increased frequency of extreme weather events is likely to be unfavourable for crop production, horticulture and forestry, and various measures are needed to protect against these effects and to keep the production of food raw materials safe.

7.2 Recommendations

General

This report is based on the current literature and shows the value of regionally focused work on the impacts of climate change on extreme weather. Effective, cost-efficient adaptation action depends critically on information about how future global warming will affect extremes of all weather phenomena. Further research is therefore required, in particular on the development of regional models for predicting possible changes to patterns of extreme weather.

Sectors

The different impacts of extreme weather each require adaptation actions tuned to dealing with specific impacts, with specific requirements for data and information and the development of climate service networks at both European and national levels.

Given that impacts of heat waves are highly variable across Europe, further studies of the factors at stake in the variability of human exposure are required. In particular this will require an understanding of differences in indoor environments and the impacts these have on health outcomes during heat waves.

There is an urgent need to share good practice in flood preparedness across Europe. Early-warning systems have been greatly strengthened in recent years but there remains a need to understand differences in responses within societies to information about flood preparedness and flood warnings.

Across Europe, planning authorities have different policies on zoning for flood defence and it would be useful to study the results of these varying approaches to ensure that best practice is identified and disseminated.

In order to improve the resilience of European agriculture, urgent action is required, as follows:

- after the approval of national or regional adaptation strategies, it is essential to establish action plans that define – together with a time schedule – which handbooks or guidance manuals covering which topic should be produced;
- handbooks for the most vulnerable sectors should be produced as a priority;
- change in extreme weather should be considered in adaptation measures, even if the changes are not yet clearly understood. Strategies based on the principle of 'no-regret and flexibility' and other anticipatory measures would lead to more resilience of the sector;
- handbooks and guidance manuals must be as specific as possible. Check-lists and good practice examples are most valuable.

Strengthen European research and dissemination collaboration

The JPI-Climate initiative is designed to contribute to highly coordinated knowledge development by improving scientific expertise on climate-change risks and adaptation options, and by connecting that knowledge with decision making on safety and major investment in climate-vulnerable sectors in Europe. JPI-Climate also acknowledges that understanding and responding to climate change requires coordinated and large-scale European efforts in research, innovation and governance.

- Our key recommendation is to continue to strengthen European climate-research communities and to build networks across borders and disciplines. Instruments are *FP7/Horizon2020, COST*, and *ECRA* (European Climate Research Alliance, www.ecra-climate.eu), and it would be valuable were connections between the results and findings of the different projects and programmes improved, and if the knowledge gained could be made more visible.
- For research on extreme events, we recommend strengthening cross-disciplinary links between the traditional climatology community and other communities such as statistics, hydrology, engineering, economy, and social policy.
- There is an urgent need to improve regional climate representation in global climate models (Racherla *et al.*, 2012) and make more comprehensive assessments of both the minimum scales at which they are applicable and their ability to predict evolution of climate variables over time. For climate

extremes, it is not sufficient to be able to describe the change in the mean quantities, but the models must demonstrate skill in describing the phenomena leading to extremes, such as storm track location, intensity and frequency. The models must also be able to capture changes to cloud generating processes and the prevalence of convective and stratiform clouds. Climate models are not expected to reproduce the observed statistics of extremes, since they provide a description of a volume rather than point values recorded by rain gauges and thermometers. Downscaling procedures, however, can be designed to bridge the results from climate models to observed statistics (Benestad *et al.*, 2012b).

Strengthen the basis for informed action and knowledge about climate

As noted by JPI-Climate, research, knowledge dissemination and innovation are crucial in helping to confront the challenges associated with climate change and generate new opportunities for sustainable development. This knowledge comes from climate sciences, and involves long-term and dedicated monitoring of the environment, requiring traditional station-based measurements as well as satellite missions. The knowledge is also dependent on infrastructure to collect and analyse the data, and a flow of information. Not least, our knowledge is built on climate simulations.

- Our recommendation is to ensure long-term support for the monitoring and upkeep of the necessary infrastructure for data collection, analysis and monitoring.
- The value of data will be enhanced by combining information from different sources, and we recommend a greater degree of data-sharing and open-data policies.
- For local climate projections, it is important to optimise the available information, which implies using different downscaling strategies that draw information from different sources and have different strengths and weaknesses. In particular, it will be important not to rely only on RCMs or empirical-statistical downscaling.

Strengthen the information basis for decision making within society

The WMO has called for a global framework of climate services (GFCS), and JPI-climate intends to improve joint European actions on climate services. There are many different agendas, and climate services are linked to political views and commercial interests. Nevertheless, society has to make tough choices about the nature and scale of its response to climate change, and it is important therefore that society has free and ready access to the information on which to base its decisions.

- Our recommendation is that the data needed for policy making and for describing the state of our environment/climate should be made freely available.
- The scientific findings and conclusions that are used as inputs for decision makers should be transparent and consist of published results. These publications should also be freely available.

Strengthen traditional scientific pillars

A large portion of the research done in Europe is organised through projects that are funded through competitive tender. This system favours progress in increasing the knowledge of well-defined issues, and provides information for specific use. Progress is ensured through milestones, deadlines, and deliveries. However, if most scientific resources are dedicated to such activities, other aspects of research may suffer, for example, the replication of published results, peer-review, scientific debates and general quality control. Furthermore, research projects tend to focus on specific, narrow questions and it is often difficult to obtain resources for cross-disciplinary research with a wider frame that is needed to provide a more complete account of climate change and its impacts. There is need for both generalists and specialists.

- Our recommendation is to raise the profile and to improve the recognition of the value of activities such as peer review, quality control and replication of previous findings.
- We also recommend that published and previously obtained results are revised in the light of new data and insights, and that controversies concerning scientific issues are, as far as possible, resolved by replication and further testing.

Continuous work, with new data and improvement of models

Climate models have proved of immense value in providing the basis for understanding climate and its future but there is still room for further development, to account for some climatic phenomena that remain imperfectly understood, and to improve modelling of the local climate. The following improvements are required, although it is recognised that this sets a large agenda. The pace of progress will, to a large extent, depend on the value society places on the evidence-base for climate policy.

- The reliability of Earth System models (ESM) must be studied further. Can these be improved by higher resolution or improved numerical algorithms? More focused studies concerning parameterisation schemes, ocean-land-atmosphere couplings and feedback processes should be commissioned.
- Further study of naturally occurring phenomena and comparisons between model simulations and observations to elucidate interdependencies is needed. Larger experiments are required, with a diverse set of models to explore the links between sea ice, the stratosphere and natural phenomena, including extremes.
- The establishment of better analytical tools for understanding how different processes are interconnected in the climate system, based both on physics and statistics is required. In one particular case, better tools are needed to trace energy and mass (moisture) flows and to search for systematic dependencies.
- Better understanding is required of some vital processes, including the hydrological cycle, storm tracks and the NAO, ocean circulation in the North Atlantic and trends in sea ice.

Recommendations for society, scientific communities and science policy makers

Climate-change adaptation has to become a continuous process that relies on continued monitoring of the state of the climate and the environment. Hence, sustained Earth observations, analysis and climate modelling are integral parts of a robust and flexible climate-change adaptation strategy.

There may be many barriers to adaptation, including psychological, commercial, institutional and knowledge barriers. For climate-change adaptation, it is important to consider the range of different factors that affect vulnerability, including human factors, and to use the best possible information about the extreme weather conditions that will test this vulnerability. It is important in this to recognise the quality of the information from the current generation of climate models, recognising that they have their limitations in predicting future changes in extreme weather. Climate models, however, are still evolving and improving, and new generations of climate simulations are designed to provide more accurate and geographically differentiated information. However, it is important to act on such information as is available, as the stakes are high and decisions on investment in adaptation is needed now. We therefore strongly encourage governments to act, even though there is a measure of uncertainty, through both mitigation and adaptation measures, in order to reduce the risks associated with future climate change.

GLOSSARY

Adaptation: strategies to meet future challenges, involving changing practices or construction of new and more resilient infrastructure. The objective is to reduce vulnerability. Adaptation has a local or regional focus as opposed to removing the cause of the problems. Adaptation deals with coping with consequences rather than solving underlying problems (mitigation).

Advection: the horizontal transport by means of being embedded in moving air.

Anomalies: departures from the climatology, and describe how much a certain variable differs from its normal state.

Baroclinicity: the degree of misalignment of the gradient of pressure compared to that of the gradient of density in a fluid, and is a measure of the stability of an air flow. Cyclogenesis in the mid-latitudes is a result of baroclinic instabilities.

Beaufort Scale (Bft): an empirical measure of wind force, relating the wind speed to its effects on land or sea. The Beaufort Scale ranges from 0, which is a calm, to 12, which is a hurricane-force wind. Damage to buildings can be expected at winds exceeding 8 Beaufort and losses at sea above 6 Beaufort.

Clausius-Clapeyron equation: a way of describing the transitions between phases of a liquid or solid in relation to temperature.

Climate change: persistent and systematic changes in the typical weather patterns, but it is different from climate variability which is associated with short-term fluctuations in climate. Whereas climatic variations include El Niño Southern Oscillations and influences from volcanic eruptions, climate change is associated with long-term changes in the Earth's energy balance due, for example, to changes in atmospheric composition. Climate change involves changes in both physical processes such as energy flow and in climate statistics. In statistical terms, the climate is described in terms of a pdf, and a change in a pdf is by definition a climate change. Global warming is a climate change, but climate change does not necessarily entail global warming.

Climate-change factor: loosely used to describe the magnitude of a climate shift through simple estimates of likely change, based on a principle similar to the delta change method. The factor describes some percentage change compared to the present state, whereas the delta change method refers to an incremental change (difference).

Climate models (global and physics-based): lines of computer codes used to solve a set of mathematical equations describing the laws of physics relevant to the atmospheric and oceanic circulation, the distribution of heat and the interaction between electromagnetic radiation and atmospheric gases. Climate models constitute our theoretical knowledge of the climate system, describing interconnections between processes. The models include a description of cloud processes, land-surface characteristics and the chemical composition of the atmosphere. They consist of different modules describing the atmosphere, oceans, sea-ice/snow and the land surface, and represent the world in terms of boxes stacked next to and on top of each other. The values for temperature, motion and mass are solved in each of these boxes, based on well-known physical laws.

Climate model simulations: results from computations of climate models, often where the atmospheric greenhouse-gas concentrations, incoming solar energy, land-surface changes and/or volcanic eruptions have been specified. The mathematical equations embedded in a climate model are solved using approximations, and there are different numerical schemes for solving continuous equations in terms of discrete numbers. Sometimes, the solutions of the mathematical equations are extremely sensitive, and small differences, such as rounding errors, can lead to different outcomes after a few days (the 'butterfly effect'). Many of the mathematical equations are highly non-linear, and the circulation has a chaotic character, which is seen both in climate models and in the real world. Many of the real meteorological and climatological phenomena are reproduced in the climate models: the Hadley cell, westerlies, the NAO, cyclones, the jet stream, ocean currents, El Niño Southern Oscillations. Some phenomena are less well reproduced, such as the

Madden-Julian Oscillation and the South Asian Monsoon. Small-scale processes such as tornadoes, lightning and hailstorms are absent in these simulations.

Climate services: a concept used to describe the provision, often in a user-supplier dialogue, of climate-relevant information and knowledge, involving database access for climatological observations/measurements, scenarios/ projections, analyses and interpretations to support decision making.

Climate zones: regions with similar climate characteristics.

Climatology: can be defined as the science of climate, but is also used in the meaning of the normal climatic state such as a base line over the normal period. Climatology is often taken as the mean value for a given month over, for example, 1961-1990.

Confidence terminology used by IPCC

Confidence terminology	Degree of confidence in being correct
Very high confidence	At least 9 out of 10 chance
High confidence	About 8 out of 10 chance
Medium confidence	About 5 out of 10 chance
Low confidence	About 2 out of 10 chance
Very low confidence	Less than 1 out of 10 chance

Classification of the confidence in our knowledge:

Virtually certain:	99–100 % probability.
Very likely:	90–99 % probability.
Likely:	66–90 % probability.
About as likely as not:	33–66 % probability.
Unlikely:	10–33 % probability.
Very unlikely:	1–10 % probability.
Exceptionally unlikely:	0–1 % probability.

However, the IPCC emphasises that likelihood may be based on a quantitative analysis or an elicitation of expert views. Individual papers within the field of climate science have increasingly used a wide range of rigorous statistical approaches (Solomon *et al.*, 2007).

Convection: ascending air. Warm and moist air is lighter than dry and cold air, and the Earth's energy inception at the surface in addition to the presence of water (oceans) implies frequent unstable conditions with warm and moist air below drier and colder air. Convection usually results in clouds and precipitation, and plays an important role in both the hydrologic cycle and in the energy flows on Earth.

Convective available potential energy (CAPE): the buoyancy of air, defined as the amount of energy a hypothetical air parcel will have if it is lifted a vertical distance up through the atmosphere. CAPE provides an indication of vertical atmospheric stability and is sometimes used in predicting various weather phenomena.

Cyclogenesis: the process through which cyclones (storms) are formed initially, often through baroclinic instabilities (see baroclinicity).

Design floods: hypothetical floods that have a small probability of taking place over a certain time-scale. These are used as a yardstick for designing structures and are estimated on the basis of return-value analysis and extreme value theory modelling. They represent the flood magnitudes that a construction is built to withstand.

Downscaling: a generic term for inferring local quantities on the basis of large-scale conditions. Local climate conditions are part of a larger picture, such as the climate pattern of the surrounding region. Furthermore, the character of the local climate is strongly dependent on local geographical parameters. Climate models are known to have a minimum scale at which they give well located and accurate information, known as the minimum skilful scale, which is typically larger than the grid-box sizes. Hence, local climate information cannot be inferred directly from climate models, but can be inferred indirectly through downscaling, where the information about the dependency on the large-scale situation and the local geography is utilised. Downscaling is the process of linking local conditions to their large-scale environment. The reason for downscaling is that the global climate models are not designed to provide accurate details of local climates, partly due to their coarse representation of the world, typically a 100 km by 100 km mesh grid, and partly due to how the models compute the results, using simplified ways of describing the surface, clouds, etc. All climate models have a minimum skilful scale that is greater than their resolution (~8 by ~8 grid boxes). The rationale behind downscaling is that climate anomalies do not vary rapidly in space, and that the local climate can be expressed mathematically as a function of both geography and the large-scale conditions.

Drought: a temporary dry period, in contrast to the permanent aridity in arid areas. While there is no universal definition, drought is often classified into the following three types:

- meteorological drought: defined as prolonged abnormal deficit of precipitation;
- agricultural drought: also soil-moisture drought – a precipitation shortage during the growing season that affects agriculture or ecosystem functions;
- hydrological drought: below-normal stream flow, lake and groundwater levels.

Integrated approaches define droughts not only as a lack of rain but more generally as an excess of demand (potential evapotranspiration and runoff) over supply (precipitation), which is a first-order approximation for the drying of the land surface (Gregory *et al.*, 1997). There is a wide variety of different drought indices, which, depending on their use, differ in combining information on precipitation, evapotranspiration, runoff, temperature and soil moisture. Depending on the type of drought considered, conclusions regarding regional trends may differ (Dai, 2011b).

Dynamics: the evolution of physical processes in time, such as how circulation patterns evolve from one weather situation to the next. In climate modelling it is distinguished from thermodynamics by referring to the Navier-Stokes equations describing physical motion and the equations of momentum (Newton's laws), as opposed to changes in thermal energy.

Electromagnetic radiation: the same as light, both visible and invisible depending on its frequency/wavelength – gamma-rays, X-rays, ultraviolet light, visible light, infrared radiation, microwave radiation, radio waves. It represents a form of transport of pure energy, which can be considered as both particles (photons) and waves.

El Niño Southern Oscillation (ENSO): a tropical phenomenon related to the strong coupling between the ocean and the atmosphere, through the effects of sea surface temperatures and wind. ENSO has two phases, *El Niño* and *La Niña*, but varies in regularity. The phases usually peak around Christmas, but occur irregularly in terms of the year they appear in. The typical time scale of ENSO is 3–8 years. ENSO affects about half of the globe, but does not have a strong direct effect on the weather in Europe.

Empirical-statistical downscaling (ESD): a generic term for deriving information about local climate (predicted) from a prescribed large-scale situation. Common for these methods is a calibration stage, based on statistical means, where past inter-dependencies are identified and then used to predict local values under different circumstances. ESD is based in a different philosophy to RCMs: whereas RCMs are based on known physics relevant to the atmosphere, coded in terms of computer lines, ESD makes implicit use of the information encoded in observations, including unknown processes not accounted for in the RCMs. ESD makes the assumption that the dependencies identified in the past will also be valid in the future. ESD is far less computationally demanding than RCMs and is therefore well-suited for screening purposes of large ensembles of GCM simulations and long time-series. ESD depends critically on the availability of ground observations, for example of local temperature or precipitation, and the data quality. However, it does not produce a complete and coherent picture of the local climate in the same way as RCMs. ESD can also provide more than projections, and should be viewed as an advanced method for the analysis of GCM results.

Ensemble: used to describe a set of climate model simulations. In some cases, one climate model may be used to make many different simulations and hence provide an ensemble from one model. Alternatively, many different models may provide simulations for the same situation (e.g. the corresponding emission scenario) to construct multi-model ensembles. The ensembles can be used to provide an *ad hoc* description of uncertainties and a crude picture of conditional probabilities, although it is important to recognise that ensembles are samples of opportunity and cannot alone provide proper probability estimates. Furthermore, it is important to realise that the mean of all ensemble members (ensemble mean) brings out the common traits, such as trends, but provides a description with underestimated variance. Usually, the models describe non-linear and chaotic behaviour, where the internal variations, spontaneous variations due to past conditions rather than external influences such as ENSO and NAO, are uncorrelated amongst the members.

Extreme weather events: occur rarely – normally as rare as or rarer than the 10th or 90th percentile. They can also be defined according to their intensity: Events characterised by relatively small or large deviations from the norm. Severe: Events that result in large socio-economic losses. Severity is a complex criterion because damaging impacts can occur in the absence of a rare or intense climatic event. Common to most extreme events is their inherent irregular nature.

Extreme precipitation: expresses large precipitation amounts or intensities, or long-duration dry spells. Even though droughts can be considered as extreme precipitation events, we address here mainly events of increased precipitation intensity. By definition, it rarely occurs in the prevalent climate. The potential damaging effects are implied by the rare occurrence as neither nature nor society are prepared for the conditions. Usually one relates the degree of extremeness to the expected return period of incidents estimated from regular observations.

Floods: extreme situations with an unusually high volume of water present over a given region. There are various forms for flooding – coastal inundation (storm surges), fluvial floods, flash floods, snow-melt floods, etc.

Flux: a physics term describing a rate of transfer of energy, mass, momentum, or electric charge.

Fujita Tornado Scale: a recognised scale of the severity of a tornado from F0, light damage, to F5, incredible damage. Considerable damage is F2.

Geophysical disasters: refers to calamities caused by volcanism, earthquakes or tsunamis. Geophysical events refer to these events and do not necessarily imply a human consequence.

Global warming: a form of climate change where the global mean temperature rises.

Greenhouse effect: the situation in which the atmosphere lets visible light, a pure form of energy, from the sun penetrate to the surface, but absorbs infrared radiation and is opaque for certain frequency bands of electromagnetic radiation. In the long run, there is a balance between the energy received from the sun and the energy lost to space in terms of infrared radiation. The energy that the Earth loses to space is infrared emission emanating from air at heights above the surface rather than directly from the surface, and the greenhouse effect directs some of the infrared emission from the air back towards the surface, causing temperatures at the surface to be higher than they would be in the absence of a greenhouse effect.

Hadley cell: the Hadley cell is a tropical atmospheric circulation that is defined by the average over longitude, which features rising motion near the equator, poleward flow 10–15 km above the surface, descending motion in the subtropics, and equatorward flow near the surface. This circulation is intimately related to the trade winds, tropical rainbelts and hurricanes, subtropical deserts and the jet streams (http://en.wikipedia.org/wiki/Hadley_cell).

Heat waves: persistent hot conditions (extreme temperatures) often associated with drought and high-pressure blocking. Typically, a heat wave is declared once it has been hotter than a particular temperature for a number of days, though there is no universal definition. The threshold temperature should be defined according to the impact of interest and the local adaptation level.

Homogenisation: the process of eliminating non-climatic influences on climatic measurements. It may mean accounting for increased urbanisation, changes in instruments or practices.

Hydrological cycle: the circulation of water from evaporation over the oceans, condensation into clouds, precipitation, absorption in the ground and the biosphere, evapotransportation and river and ground run-off back into the oceans. It involves hydrology, meteorology and oceanography.

Independent and identically distributed (IID): this implies that all measurements in a series follow exactly the same probability density function (pdf) and do not depend on each other, in the sense that they do not provide information about the rest of the measurements.

Impact: the consequence of weather or climatic changes.

Mesoscale: the phenomena with a spatial extent that is smaller than the synoptic scale, about 5–100 km.

Mitigation: usually refers to ways to limit climate change, such as cutting greenhouse-gas emissions.

Moistening efficiency: the fraction of moisture evaporated inside a given region relative to the moisture that flows through the region. These two quantities depend on the size of the given region, and if the Earth's surface is separated into equally sized regions the quantities will indicate important properties of the hydrological cycle related to precipitation and its possible change.

Natural hazards: include natural phenomena that have detrimental consequences for people, society or ecosystems. A natural hazard will not result in a disaster in areas without vulnerability, for example strong earthquakes in uninhabited areas. Typical examples include floods, tornados, hurricanes, volcanic eruptions, earthquakes, heat waves and landslides.

North Atlantic Oscillation (NAO): a recurring spatial pattern of mean sea-level pressure (MSLP) characterised by low MSLP over Iceland and high over the Azores/Lisbon. The NAO expresses climate variability associated with variations in the large-scale temperature and precipitation pattern over Northern Europe.

Palmer Drought Index or Palmer Drought Severity Index (PDSI): a measurement of dryness based on recent precipitation and temperature. It is based on a supply-and-demand model of soil moisture. Supply is comparatively straightforward to calculate. Demand depends on temperature and the amount of moisture in the soil, as well as on hard-to-calibrate factors including evapotranspiration and recharge rates, which in the index are approximated based on the most readily available data for precipitation and temperature. The index has proven most effective in determining long-term drought – a matter of several months – and not as good with conditions over a matter of weeks. It uses a 0 as normal and drought is shown in terms of negative numbers; for example, -2 is a moderate drought, -3 a severe drought, and -4 an extreme drought. Palmer's algorithm is used also to describe wet spells, using corresponding positive numbers.

Parametrisation schemes: simple ways of describing the bulk effect of unresolved processes in climate models, typically small-scale phenomena. Parametrisation schemes are typically simple statistical models based on physical understanding and field measurements. Parametrisation schemes include representations of clouds, the boundary layer, turbulence, gravity waves, surface friction and wind stress (http://en.wikipedia.org/ wiki/Parametrization_(atmospheric_modeling)).

Percentiles or quantiles: often represented mathematically by the symbol q_p, and defined as the data value that is greater than p % of the data sample. A 95th percentile (q_{95}) is greater than 95 % of the values sampled.

Probability density function (pdf): describes the probability of a quantity having a value within an incremental interval.

Physical conditions: a term referring to physical aspects that exert influence on the climate, such as solar electromagnetic radiation and the planetary energy balance.

Positive feedbacks: processes which amplify the effect of an original forcing.

Precautionary principle: where there are severe consequences but where complete evidence is not yet available, it may be desirable to take action as a matter of precaution. This is known as the precautionary principle and it is now enshrined in EU law, for example on health and consumer protection. The precautionary principle may be invoked when potentially adverse effects have been identified, the available scientific information has been assessed but a degree of scientific uncertainty persists.

Representative concentration pathways (RCP): the latest set of four greenhouse gas trajectories used for the IPCC's *Fifth Assessment Report* due to be published in 2013/2014.

Reanalysis: the results of an atmospheric model that has used observational data to guide (constrain) it to the actual atmospheric state. Often, reanalyses use advanced methods for determining the model state known as data assimilation, and use all available data – surface observations, satellite retrievals, and data from aircraft, buoys, radiosondes and ships. The reanalyses provide the best picture we have of the present state of the atmosphere.

Record-breaking event: is defined as a measurement that has a magnitude greater than the magnitudes of all preceding values. The definition can also include events with magnitudes less than the minimum value for all preceding measurements.

Recycling ratio: the fraction of precipitation in a region that comes from evaporation to the amount that comes from moisture transported into the region. There are large regional variations in recycling. On a 500 km length scale, the global average is about 10 %, but values of ~50 % and more are estimated over sub-tropical oceans with stagnant, clear air over open water and eastern Siberia (Trenberth, 1999). Low values of < 5 % are estimated over subtropical and other arid continental regions and over tropical and extra-tropical oceans.

Regional climate models (RCMs): climate models designed for a specific region, with much in common with global climate models. Some main differences include lateral boundaries imposed on the results at the edage of the region described. The RCMs are nested into global climate model results, taking the results from the global climate models (GCMs) as boundary values. They may also differ in the way they represent cloud processes, exchanges of heat and mass at the surface, atmospheric composition, solar energy and volcanism. Furthermore, RCMs tend to include a more detailed description of orography, with higher mountains, and therefore provide a different description of the surface winds and orographically forced precipitation to that of the GCM results in which it is embedded. The RCM results tend to contain systematic errors (biases), partly due to the simplified view of the world (parameterisation schemes, lack of coupling between the lower surface and the atmosphere, etc.), minimum skilful scale, the minimum scale at which global-scale models can be expected to give good local scale prediction and the fact that the RCM results do not directly correspond to observations (the former are volume averages whereas the latter are typically point measurements). Furthermore, RCM results are prone to biases in the GCM result in which they are nested.

Regression: a statistical technique for analysing data trying to explain variations in one or more variables (the response) in terms of the variations of one or more explanatory variables. It provides a means for making simplified mathematical curves fit a set of data, and is often used to estimate the mean rate of change (trend analyses) or to find a best estimate of some coefficient of a known equation, based on observational data.

Return value analysis: a method for estimating the average recurrence time between events (return period) or the magnitude of an event (return value).

Risk: often taken to be the product of the probability of an event and the severity of its consequences. In statistical terms, this can be expressed as $Risk(Y)=Pr(X)\ C(Y\backslash X)$, where Pr is the probability, C is the cost, X is a variable describing the magnitude of the event, and Y is a sector or region.

Rossby waves: caused by flows where the velocity changes over distance (shear) on rotating planets. Their driving force involves the Coriolis force, which varies with latitude due to the planet's geometric shape and the surface inclination with respect to the axis of rotation. The manifestation of Rossby waves is large-scale (~2 000 km) meanders in the atmospheric flow, often associated with different air temperature and types. Rossby waves play a role in the genesis and persistence of low- and high-pressure systems.

Satellite retrievals: refer to remote sensing measurements made by satellites. The satellites can only record the light reaching their instruments and time, but from the different intensities of light for different frequencies can derive quantities such as temperature, gas concentrations, surface conditions (waves, vegetation, etc.), movement and particle concentrations. In addition, accurate timing and the location of the satellites can be used to estimate the Earth's gravitational field.

Spatial patterns: maps that describe how a certain variable, for example temperature, precipitation or mean sea level pressure, varies with location for a given time. The general temperature spatial pattern is characterised by cooler conditions at high latitudes and altitudes, and the spatial pattern of the NAO is characterised by a dipole structure with low pressure over Iceland and high pressure over the Azores/Lisbon.

Special Report on Emissions Scenarios (SRES): describe a set of scenarios published by the IPCC in 2000 for use in the Third Assessment Report. The SRES scenarios were constructed to explore future developments in the global environment with special reference to the production of greenhouse gases and aerosol precursor emissions. They use the following terminology: *Storyline* which refers to a narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces; *Scenario* referring to projections of a potential future, based on a clear logic and quantified storyline; and *Scenario family* consisting of one or more scenarios that have the same demographic, politico-societal, economic and technological storyline. The SRES had four narrative storylines, labelled A1, A2, B1 and B2, describing different relationships between the forces driving greenhouse-gas and aerosol emissions and their evolution during the 21st century for large world regions and globally. Each represents different demographic, social, economic, technological and environmental developments that diverge in increasingly irreversible ways.

Statistical significance: describes the likelihood of an observation or a result being due to pure chance. It is often used in connection with a null-hypothesis (an alternative explanation, usually such as there is no correlation or no causal relationship), and gives the odds that the null-hypothesis is correct.

Storm tracks: regions with a high frequency of storms. The storms tend to have a preference for the northeastern part of the North Atlantic, but are affected by the NAO.

Stratosphere: the thin layer of air above the tropopause and the troposphere where the temperature increases with height. Typically, it starts at around 10 km above sea level.

Synoptic: a spatial scale that is similar to the spatial extent of mid-latitude cyclones (storms). It usually refers to phenomena or measurements with a horizontal length scale of ~1 000 km.

Theory: a well-established fact concerning interrelations and physical laws. These include quantum physics, the general theory of relativity, Newton's laws, the ideal gas laws, thermodynamics, electromagnetism, conservation of energy and mass and mathematical truths. Whereas theories are seen as facts, hypotheses are more tentative and speculative and are not yet well-established.

Trends: long-term evolution, such as climate change and global warming. Trend analysis is used to describe trends, and can involve linear or multiple regression with time as a covariate. A trend model may be a straight line (linear) or more complex (polynomial), and the long-term rate of change can be described in terms of the time derivative from the trend model.

Troposphere: the lower active region of the atmosphere where most of the weather (clouds) is, and where the temperature decreases with height (lapse rate describes how fast the temperature drops with height). In this atmospheric region, the vertical temperature profile is strongly influenced by the hydrostatic stability, the balance between air pressure and the weight of the air: light air rises, heavy air sinks, giving rise to convection, subsidence, clouds, and circulation patterns.

Uncertainty: means lack of precision or that the exact value for a given time is not predictable, but it does not usually imply lack of knowledge. Often, the future state of a process may not be predictable, such as a roll with dice, but the probability of finding it in a certain state may be well known (the probability of rolling a six is 1/6, and flipping tails with a coin is 1/2). In climate science, the dice may be loaded, and we may refer to uncertainties even with perfect knowledge of the odds. Uncertainties can be modelled statistically in terms of pdfs, extreme value theory and stochastic time series models.

Vulnerability: the sensitivity to a hazard. According to the SREX report, vulnerability describes a set of conditions of people that derive from their historical and prevailing cultural, social, environmental, political, and economic contexts. In this sense, vulnerable groups are at risk not only because they are exposed to a hazard but also as a result of marginality, everyday patterns of social interaction and organisation, or access to resources.

Wet-bulb temperature: the temperature a parcel of air would have if it were cooled at constant pressure (adiabatically) to saturation (100 % relative humidity) by the evaporation of water into it, with the latent heat being supplied by the parcel. An actual wet-bulb thermometer indicates a temperature close to the true (thermodynamic) wet-bulb temperature. The wet-bulb temperature is the lowest temperature that can be reached under current ambient conditions by the evaporation of water only; it is the temperature felt when the skin is wet and exposed to moving air. Wet-bulb temperature is largely determined by actual air temperature (dry-bulb temperature) and humidity, the amount of moisture in the air. (http://en.wikipedia.org/wiki/Wet-bulb_temperature)

Wind storms: For Germany, wind speeds equal to or higher than Bft force 8 (sustained wind speeds > 17.2 m/s) roughly define a wind storm. This value, which is based on the experience of the insurance industry, is approximately equivalent to the 98th percentile of wind speed over the plain-land areas in northern Germany.

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APPENDIX I IMPORTANT HISTORIC EXTREME EVENTS

Extreme weather events since 1999

December 1999: Winter storms in Western and Central Europe. Heavy precipitation and extremely high wind speed.

August 2002: Heavy precipitation and floods along Central European rivers. Economic losses exceeded €15 billion.

Summer of 2003: Heat wave in Central and Western Europe. Extremely high temperatures for weeks led to more than 30 000 deaths and extreme drought across Europe. More than 25 000 fires burnt 650 000 hectares.

Summer of 2005: Heat and drought in Southern Europe. Extremely high temperature. Significantly less precipitation than average.

Winter of 2006: Extreme cold in Eastern and Central Europe. Minimum temperature was 4–12° C colder than the 1961–1990 mean.

Mild winter of 2007: Winter of 2007 ranked among the warmest ever recorded in a large part of Europe. Average temperature anomalies were more than 4° C.

May of 2008: Flash floods in Central Europe.

Summer of 2008: Floods across Eastern European river. Nearly 50 000 homes were submerged; more than 30 000 hectares of farmland was destroyed.

Winter of 2009: The winter of 2009 was colder than usual in Central and Western Europe.

Spring of 2010: Flooding in Poland and Eastern Europe. In May 2009 the precipitation amount was 100 mm above the long-term mean across vast regions of Eastern Europe. Total flood damage exceeded € 2.5 billion.

Winter of 2010: Unusually cold, snowy winter in Europe. Most areas of Europe saw between 10 and 20 additional ice days than normal from December through February. Due to the prolonged cold temperatures and the frequency of snow storms, the number of days with more than 1 cm of snow on the ground was significantly greater than normal across Europe.

February of 2010: Severe winter storms in Europe. Tropical storm Xynthia passed through Portugal, Spain, France, Belgium, the Netherlands and Germany, causing heavy rainfall and high wind speed.

Summer of 2010: Heat and drought in Eastern Europe. This region was hit by record temperatures; very low rainfall amounts resulted in crop losses, peat and forest fires. Mean temperature was between 4 and 8° C higher than the long-term average during July and August. For many regions there were at least 10 and up to 30 more summer days than normal during July 2010.

Source: European Climate Assessment & Dataset, 1999 (ECA&D, http://eca.knmi.nl).

APPENDIX II AGRICULTURAL IMPACTS OF EXTREME WEATHER

REGION	CLIMATE CHANGE	IMPACTS
Mediterranean	Increasing temperature	Heat waves, drought
	Increasing maximum temperature	Heat stress
	Increasing minimum temperature	Pests and diseases, decreasing frost damage
	Decreasing rainfall	Drought, limited water availability
	Longer, more intensive dry periods in summer	Forest fires
Atlantic	Increasing minimum temperature	Decreasing frost damage
	Hotter, drier summers	Faster ripening, shorter vegetation period
	Increasing winter precipitation	Floods, water-logging hazards
Baltic	Increasing maximum and minimum temperatures	Increasing crop potential, longer vegetation period, permafrost thaw, pests and diseases
	Increase in extreme precipitation in summer	Floods, decreasing crop safety
	Increasing sea and lake levels	Water-logging
Central and Eastern Europe	Increasing winter precipitation	Floods and water-logging
	Decreasing summer rainfall	Limited water availability, drought
	Increasing rainfall intensity	Flash floods, limited water utilisation, erosion risk
	Increasing temperature	Drought, shorter vegetation period
	Increasing wind speed	Crop safety problems, soil erosion

APPENDIX III EXTREME WEATHER PROTECTION MEASURES FOR AGRICULTURE

CLIMATIC VARIABLE	EXTREME WEATHER PHENOMENON	POSSIBLE ADAPTATION MEASURES
Precipitation	Too much precipitation	Flood protection Construction and maintenance of drainage systems Establishment of emergency reservoirs for flood waters Use of immersion-tolerant species or varieties in critical areas
	Too little precipitation	Construction of reservoirs Placement and maintenance of irrigation systems and equipment Protection against salinisation (groundwater management, irrigation water quality)
	Intensive rainfall	Maintenance or enhancement of forest coverage Cultivation of crops providing good ground cover on sloping areas Strict adherence to the required tilling direction Construction and maintenance of drains Maintenance and enhancement of soil organic matter reserves
	Hail	Use of anti-hail nets in orchards and vineyards Use of anti-hail cannons Use of anti-hail rockets
Temperature	Low winter temperature	Selection and cultivation of frost-tolerant plant varieties
	Early spring frosts	Avoidance of areas prone to frost when choosing cultivation sites Choice of crops suited to the site conditions Active defence against frost (use of smoke, heating, anti-frost sprinklers,frost fans)
	High temperature	Irrigation and satisfactory soil water supplies
Wind storms		Strict adherence to the required tilling direction

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Extreme Weather Events in Europe: preparing for climate change adaptation

MET Norway & DVNA in cooperation with EASAC