SMHI

CLIMATE EXTREMES FOR SWEDEN

State of knowledge and implications for adaptation and mitigation
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CONTENT

»Extreme: reaching a high or the highest degree, very great; not usual; exceptional; very severe or serious« (Oxford Dictionary, 2018).

1. INTRODUCTION: WHY DO EXTREMES MATTER?

Extremes of weather and climate are part of the human experience with nature. Societies have always been vulnerable to e.g. flooding, extreme precipitation, windstorms and heat waves, and sought to adapt in order to avoid extreme impacts on living conditions.

The term "climate" describes the long-term state and behaviour of the climate system and the atmosphere, typically the 30-year average of weather, as well as anomalous and rare events on top of the long-term average. "Climate extremes" are generally defined as the occurrence of a climate variable above (or below) a certain threshold value near the upper (or lower) range of observed values. Both extreme weather and extreme climate events are collectively referred to as climate extremes (Field et al., 2012). IPCC further distinguishes between "Weather and Climate Extremes" (such as precipitation, temperature incl. hot/cold spells, wind) and "Impacts on the Natural Physical Environment" (such as floods, droughts, sea level and more).

While the mean climate is changing and the transformation can be largely attributed to anthropogenic emissions (Field et al., 2012), climate extremes are changing as well. The character and severity of impacts from climate extremes depend not only on the extremes themselves but also on exposure and vulnerability of societal structures. Therefore, for this report, the overarching definition of an extreme is extended by the perspective of users and their respective vulnerabilities. The complete resulting definition of a climate extreme becomes case sensitive and diverse, and needs to be set for individual cases. It includes even temporal sequences of events or compound events involving combinations of several meteorological and hydrological phenomena and variables, each not necessarily extreme by itself, which together constitute an extreme impact (Leonard et al., 2014). Accordingly, exposure and vulnerability in Swedish municipalities, enterprises and other societal sectors vary dependent on the specific nature of climate extremes and the sectoral risk.

Based on existing scientific literature, there is clear evidence that the climate and its extremes are changing (e.g. Westra et al., 2014; Lehmann et al., 2015; Schleussner et al., 2017) in a way that goes beyond our present experience and that exceeds our preparedness, i.e. our adaptation level (e.g. Im et al., 2017). Changes of extremes such as hot/cold days, warm-spell duration, heavy rainfall, aggregated over global observational networks exhibit an increase that is substantially larger than what would be expected by chance (Schleussner et al., 2017) in a stable climate.

There is high confidence that certain observed changes in temperature extremes can be attributed to anthropogenic forcing (Masson-Delmotte et al., 2018; Bindoff et al., 2013). Enhanced extreme peaks in a number of additional climate variables on a global scale can be attributed to the changing climate. Attribution of extreme events is a growing field of science and there has been a rapid increase with time in the number of peer-reviewed papers (such as collected by Herring et al., 2019).

On a local scale it still can be difficult to determine if a specific extreme event is attributable to the overall climate change. Often, available observational records are not long enough to statistically attribute single events based on observations only. Methods for local attribution, involving climate models, have been further developed and quasi-operational services for event attribution are on the way to become established. As an example, recent cases of extreme events have been analysed at https://www.worldweatherattribution.org/.

An example relevant to Sweden is the extremely dry period in Northern Europe during spring and summer 2018, with all-time-high temperatures at many locations since the start of observational records. Vogel et al. (2019) conclude that it is virtually certain (using IPCC calibrated uncertainty language) that the 2018 northern hemisphere concurrent heat events would not have occurred without human-induced climate change.

In the near future it might be possible to offer rapid assessments of global warming's connection to particular meteorological events with full public reports several weeks after an event (Schiermeier et al., 2018).

The knowledge about climate and weather extremes, its underlying mechanisms, trends and attribution is highly relevant in order to consider the risks and vulnerability for most societal sectors to changing extremes. This knowledge synthesis compiles and communicates a condensed and balanced exposition of scattered available information concerning recent and possible future climate extremes in Sweden, serving growing societal expectations on climate adaptation. Information sources are drawn from the Nordic region and climatologically similar regions, as well as from Europe and the rest of the world where applicable.

Before this report, climate extremes and their impacts have been described both from a natural science perspective and from an impact and risk management perspective. Several assessments including coverage of climate extremes exists, some of them have a global scope or provide general information (e.g. Field et al., 2012; Pachauri et al., 2014), others have a more continental perspective (e.g. AMAP, 2011; Hov et al., 2013; BACC, 2015; EEA et al. 2017), while a few have a Swedish focus (Holgersson et al., 2007; Kjellström et al., 2014). However, with the rapid advancement of scientific knowledge from numerous climate research projects, and as a consequence of recent episodic climate extreme events, the information in such reports is not up-to-date or not focused to fulfil Swedish stakeholders' requirements. This report attempts to close these gaps as far as possible, and to document remaining gaps.

Major climate variables covered in this report are precipitation, floods, droughts, wind and storminess including thunderstorms and tornadoes, hailstorms, ice storms, freezing rain, heat waves and cold spells. Wind storms are many times the ground for different types of extremes, such as heavy winds, precipitation, hale and snow events. Therefore, storm events are treated more detailed than most other extreme conditions in this report. This report is also meant to support informed risk management and development of communication strategies by stakeholders.

Questions relevant for stakeholders are:

- What kind of change in extreme conditions can we expect from global warming?
- Will certain types of extreme conditions become more frequent?
- Will extreme events under recent climate conditions become more or less intense?
- How do changing extreme conditions impact on the stakeholders sector?
- How does impact and vulnerability translate into best measures for adaptation to and mitigation of climate change?

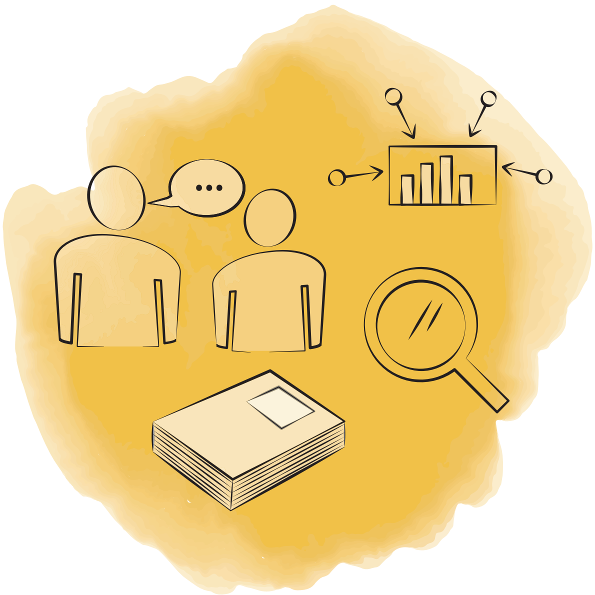
The synthesis report is expected to:

- Provide Swedish stakeholders from local to national level with knowledge on climate extremes to facilitate estimation of the impact potentials.
- Facilitate communication of climate extremes in recent and future climate.
- Facilitate translation of changing climate extremes to sectoral risk management and resilience analyses, and associated options for climate adaptation and mitigation.
- Provide examples of helpful best practises for communication of knowledge on climate extremes.
- Identify knowledge gaps and research needs related to climate extremes to support capability development for adapting to and mitigating climate change impacts with maximum efficacy.

Communication of scientifically founded knowledge about climate extremes needs a strategy that depends on the expected impacts themselves, and on stakeholders' perception of risks. Therefore, interaction between providers and recipients of information is necessarily a participatory process and is an integral part of this report.

Climate extremes are an important topic also in conjunction with the Paris Climate Accord. Mitigation measures need to be planned rather quickly, which requires knowledge on climate extremes themselves and how they depend on connected decision options for climate actions. The synthesis parts regarding future climates are expected to help identifying remaining needed research to better judge the consequences of alternative mitigation options for Sweden.

This report is written for a professionally interested audience in public and private societal sectors and in the climate science community, including local to national administration and governance and organizations in economic and financial entities. The report is written in English to allow international usage despite the clear focus on Sweden.



»Reviews provide a means by which development research can be combined to provide greater value than the sum of its parts.« (Stewart, 2014)

2. METHODS AND PROCEDURES FOR THIS SYNTHESIS REVIEW

This section explains the overall methods of gathering the knowledge for this synthesis. It clarifies the selection of literature and describes how the stakeholder communication for this particular synthesis was planned and conducted, as well as the results and outcomes of those activities. The information we use is extracted from:

- Peer-reviewed, scientific literature, on climate extremes
- Gathering of expertise from stakeholder knowledge – the user's perspective.
- Other literature, so called grey literature, related to the extremes, and national and international websites showcasing cases dealing with adaptation to climate change to serve as inspiration to the reader.

2.1 SELECTION OF PEER-REVIEWED, SCIENTIFIC LITERATURE, ON CLIMATE EXTREMES

This synthesis is based on a selection of sources of information. We have selected the Rapid Evidence Assessment (REA), also referred to as a rapid review, as our method to assemble literature within the scope of climate extremes in Sweden. The Rapid Evidence assessment includes a structured, stepwise methodology to comprehensively collate, critically appraise and synthesise existing research evidence (traditional academic and grey literature), following a systematic review methodology but with components of the process simplified or omitted to produce information within a limited project time (Collins et al., 2015). Compared to a systematic review, the REA tends to be less ambitious in scope, with a narrower regional or topic focus. Pragmatic decisions are made about what can be achieved in a limited time, and steps are taken to ensure rigour is maintained despite the tight time frame (Stewart, 2014).

The literature available in this field is vast. Over 300 000 records (articles, book chapters etc.) were found in Web of Science, when a search was done combining climate change, climate extremes, mitigation to climate change and adaptation to climate change. The picture narrows down when a geographical filter (covering the Nordic countries) is added, with an amount of just over 11 000 records or scientific articles, books and chapters in books. Several of these records include also paleo climatic environmental changes. After excluding past geological extremes 386 records remained.

2.2 GATHERING THE EXPERTISE FROM STAKEHOLDER KNOWLEDGE – THE USER'S PERSPECTIVE

The advisory board for this synthesis consists of professionals from a selection of sectors and knowledge backgrounds:

- Lotta Andersson (SMHI),
- Cecilia Alfredsson (MSB),
- Karl-Erik Grevendahl (Karl-Erik Grevendahl Development AB Consultants),
- Kaj Hellner (Länsstyrelsen i Södermanland),
- Barbro Näslund Landenmark (MSB),
- Katarina Skoglycka (Oskarshamn municipality),
- Roger Street (UKCIP - UK Climate Impact Programme),
- Rob Swart (Wageningen University, The Netherlands).

Two of the board members are internationally engaged in the climate services sector and with long experience in climate change related vulnerability, impact and exposure, risks related to climate change and adaptation. Further, two members come from Swedish national authorities with a good insight on the national agenda of climate change related discussions – The Swedish National Knowledge Centre for Climate Change Adaptation (located at the Swedish Meteorological and Hydrological Institute, SMHI) and the Swedish Civil Contingency Agency (Myndigheten för samhällsskydd och beredskap, MSB). Both national authorities are very much involved in preparing useful information and knowledge for society on climate change and extreme events. The Swedish Civil Contingency Agency further has the task to inform municipalities and give advice on how to tackle different risks of extreme events, such as flooding, heat waves etc.

Sweden has 21 County Administrative Boards, which actively work with supervision of Swedish rules and laws. One of these representatives, specifically working with adaptation to climate change, was also engaged as an advisory board member. To capture the voices of the municipalities in Sweden, one advisory board member, with expertise from climate change and energy and adaptation, was engaged. The private sector was included in the advisory board by a consultant coordinating several networks within environmental and climate issues, and a strong focus on the needs of the small and medium sized companies in southern Sweden.

The Advisory Board was contacted by phone and email during early 2018. They all received the first outline of the synthesis and were asked to kindly give written feedback on general logic of the set-up of the chapters in the outline, discuss the selected extremes for the project, if possible give good examples of dealing with climate extremes, including giving examples of grey literature, and important knowledge gaps related to climate extremes. The 5th of March 2018 a workshop was held to discuss the outcomes and suggestions from the advisory board.

After the workshop the project team updated the synthesis outline with respect to comments and discussions during the workshop. All the suggestions coming from the advisory board were taken in to careful consideration, some were implemented, other were not considered feasible. Here are a few examples of suggestions, if they were implemented in this synthesis and why:

- Conduct a systematic review: the synthesis followed instead the Rapid Evidence Assessment (REA) as explained above (section 2.1).
- Inclusion of damage: information of damage from extreme events rarely exists as public information. Thus we cannot attempt a quantitative overview. Still, information about damage was included in sections 3 and 4 whenever fitting.
- Divide Sweden in regions: this suggestion was not followed, instead the synthesis discusses regions only when meaningful in the sense of literature available. For example, precipitation extremes can be detailed for southern Sweden and other regions.
- Focus on a specific future climate scenario: this suggestion was not followed, the project team decided to describe the range of scenarios and identify potential gaps, such as the limited work done for RCP2.6.
- Include a glossary to clarify some concepts: a glossary was prepared and is included in the synthesis report.
- Include impacts in specific sectors: the synthesis looked at the impacts of climate extremes on agriculture (section 4) and covers some examples of adaptation in this sector in section 5.
- Address the communication of uncertainties: this synthesis addresses the uncertainties for specific climate extremes (section 3) as well as communication aspects (section 5).

At the Nordic Conference of Adaptation a conference poster was presented with the information gathered in the project so far, together with the overall project aims, and a possibility for poster readers to interact and comment on the findings and their needs related to climate extremes (Figure A.1 in the Appendix).

2.3 GREY LITERATURE AND NATIONAL AND INTERNATIONAL WEBSITES SHOWCASING CASES DEALING WITH ADAPTATION TO CLIMATE CHANGE

Other literature, so called grey literature, related to the extremes, such as reports and documents from municipalities and national authorities, as well as non-governmental organisations or private industry networks have been gathered from our advisory group and our contacts within different levels of society. A total of 43 reports were consulted.

It is typically difficult for a user of climate information (for example as a civil servant at a municipality, or a developer within a private company) to understand how to select which information to incorporate in decision making in order to prepare for future climate extremes. Often it is found practical to look at how other companies or municipalities have dealt with a similar problem, to get an idea of things to look out for and avoid, as well as to get inspired by methods and ways to implement new knowledge.

There are several national and international websites which list or showcase such cases dealing with adaptation to climate change, research projects in collaboration with societal actors, mitigation measures taken on a local, national and international level, and company cases addressing climate change.

In this synthesis our aim was to highlight some key examples for inspiration to the reader. The first step was to list available websites with cases, to get an overview of what is available online for users of climate information relating to climate extremes. The list focuses on websites from the Nordic countries, and websites with cases explained in English (Table A.1 in the Appendix).

Based on the listed websites with cases, and the outline and focus of this synthesis, the following criteria were set up when choosing the cases for the report, presented in chapter 5:

- The cases has to relate to a problem or a solution where climate extremes are one of the factors (not climate change in general).
- The cases should preferably together cover the range of climate extremes discussed in this synthesis.
- The cases should preferably cover different economic sectors.
- The cases should be of relevance to a Swedish context - geographically, climatologically and economically.
- The selected cases should have further contact information available, so that an interested reader can learn more by contacting a key person, or finding more information in reports or articles.
- The selected cases should be fairly recent.

»A changing climate leads to changes in the frequency, intensity, spatial extent, duration, and timing of extreme weather and climate events, and can result in unprecedented extreme weather and climate events« (Field et al., 2012)

3. UPDATED STATE OF KNOWLEDGE ABOUT CLIMATE EXTREMES AND THEIR TRENDS

Basic mechanisms that lead to extreme events can formally be separated in dynamically driven (i.e. circulation induced by atmospheric patterns) and thermodynamically driven (i.e. induced by temperature and moisture at the surface) (Sillmann et al., 2017), although ultimately all weather is indirectly thermodynamically driven. This formal separation between dynamical and thermodynamic changes is used particularly in event attribution studies to better understand the underlying processes contributing to a specific extreme event (Mitchell et al. 2017; Vautard et al. 2016; Yiou et al. 2017). It is important to note that both dynamical and thermodynamic processes can be respectively relevant for generating an extreme event (Sillmann et al., 2017).

Based on existing publications, the latest knowledge about the natural science mechanisms and theory of climate extremes is collected in this section. For each extreme type, observations, their limits, and historical trends are described, including an analysis of how well extreme conditions and connected trends are simulated in climate models. In addition, expected changes of the respective extreme for the future are discussed based on climate scenarios.

Combinations of meteorological and hydrological phenomena together can constitute an extreme event, so-called compound events. Therefore combinations such as high winds in combination with extreme precipitation are described here as well, often together with the leading variables (e.g. winds).

The extremes are discussed from a Swedish or Nordic regional perspective, but taking into account possible knowledge from other regions or global scale background mechanisms.

3.1 PRECIPITATION

Background

Under a warming climate, the global hydrological cycle is expected to increase with a warming lower atmosphere due to increased evaporation particularly over water bodies. The well-established physical law of Clausius-Clapeyron dictates the maximum atmospheric water holding capacity. An increase in temperature leads to an exponential increase in water holding capacity by around 7% per degree at normal pressure and temperature. The global hydrological cycle in practice cannot increase at more than about half that rate because of energy constraints (Pall et al., 2006; Allen and Ingram, 2002), but local changes can be larger.

Extreme short duration precipitation, also known as cloud bursts has been argued to increase at the rate predicted by Clausius-Clapeyron assuming that relative humidity and dynamical motions of the atmosphere remains unchanged (Trenberth et al., 2003). However, changes in storm scale dynamics can affect this rate, and several studies have pointed to a potential super-Clausius-Clapeyron scaling of sub-daily events (see for example review by Westra et al., 2013).

Recent climate

Studies of precipitation extremes are hampered by large variability in precipitation, which demands long time series to detect extremes. Further poor sampling of smaller scale cloudburst type events in station networks, and few observations with sub-daily temporal sampling in long homogeneous time series leads to large uncertainties and few clear trends. Statistical noise is high, and aggregation over multiple gauges is mostly necessary to separate trend signals from the noisy background.

Several studies have found significant increases in extreme daily precipitation for large parts of the globe, e.g. defined as events above 10 mm/day or a high percentile. Changes over Fennoscandia are found to be significantly increasing (Groisman et al., 2005; Westra et al., 2013), only partly significantly increasing (Westra et al., 2013; Groisman et al., 2005; Donat et al., 2013; Alexander et al., 2006) or non-significantly changing (Kenyon and Hegerl, 2010; Donat et al., 2013). Lehmann et al. (2015) showed that record-breaking daily precipitation extremes are significantly increasing globally, and regionally such as in Europe.

Extremes in annual maximum daily precipitation has been found to increase in global studies (Westra et al., 2013; Groisman et al., 2005), but a recent local study with the latest update of Swedish gauge data found no significant increase, even when gauges are pooled across the whole country (Olsson et al., 2018).

Gregersen et al. (2014) studied long time series of daily precipitation data in Denmark and southern Sweden, and found oscillatory behaviour of the frequency and magnitude of extremes with a cycle of about 30 and 20 years respectively. They also found a general increasing trend over the region. The frequency of the 1% most extreme daily data for stations in northern Fennoscandia shows a weak tendency toward an increase at the end of the period 1914-2014 (Kivinen et al., 2017).

On sub-daily timescales, data records are often shorter and the statistical noise level higher, which means they are less capable to show significant changes. Further, Olsson et al. (2018) studied trends in sub-daily data of the Swedish gauge network for the last about 20 years, but found no significant changes. The 20 year period is too short for a proper trend analysis due to natural variability, and the existence of long-term trends remains inconclusive. Guerreiro et al. (2018) showed that sub-daily precipitation extremes only show significant changes when aggregated at continental scales, for a gauge network in Australia.

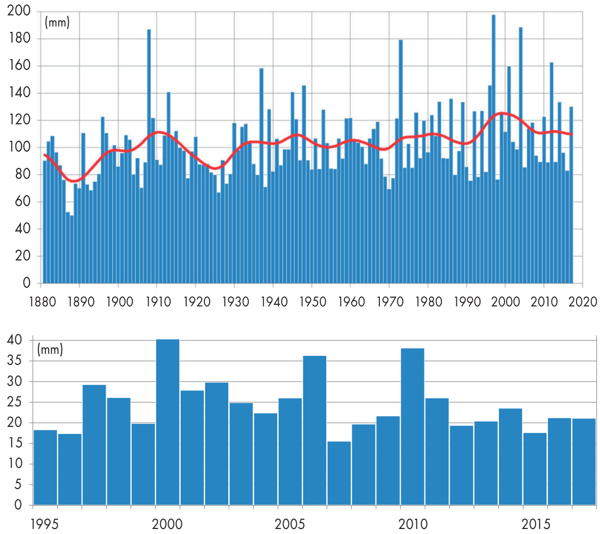


Figure 3.1: (top) Annual peak daily precipitation at any of SMHI's weather stations in Sweden: There is a slight increasing trend in the observed countrywide annual maximum daily precipitation in Sweden in the period 1880 to 2017; (bottom) Annual peak 15 min precipitation at any of SMHI's weather stations in Sweden: no significant trend can be seen in the countrywide annual maximum 15 min precipitation observations for the recent past (1995-2017). Adapted from Figures 31 and 51 in Olsson et al. (2018).

To circumvent the problems of small samples with low signal to noise ratio in trend analysis, a relationship between extreme precipitation (as a high percentile of the distribution) and surface temperature or dew point temperature has been suggested (Lenderink and Meijgaard, 2008). Lenderink and Meijgaard (2008) found that whereas daily precipitation scales at approximately the Clausius-Clapeyron rate, hourly precipitation scales at close to two times that rate. This indicates a dynamical contribution to the expected pure thermodynamic scaling, for example in the form of spatial interactions (Moseley et al., 2013) or cloud processes (Westra et al., 2013). However, the method is potentially misleading due to statistical effects of mixing precipitation types (Haerter and Berg, 2009) or different ice-free sea surfaces which gives rise to strong convective motions that lift moist synoptic conditions by being sensitive to relative humidity (Jones et al., 2010). Using dew point temperature, to remove the sensitivity to relative humidity, has made the method more robust to moisture availability and the scaling has been argued to be a predictor for future changes (Lenderink and Meijgaard, 2010). Following the Lenderink and Meijgaard (2008) method, several studies have found significant super Clausius-Clapeyron scaling in sub-daily precipitation extremes across the globe (see Westra et al. (2013) for a review).

Extreme snowfall events are generally poorly recorded due to a highly sensitivity of gauge measurements, because snow is diverted from the gauge due to turbulence around the nozzle extreme. However, there are manual measurements and estimations available for so-called lake-effect snowfall events (in Swedish "snökanoner") which occur along the Baltic coastline and the lakes Vänern and Vättern. Lake-effect events occur when cold air meets relatively warm ice-free sea surfaces which gives rise to strong convective motions that lift moist surface air and causes heavy snowfall affecting narrow strips of land (Changnon et al., 2006). The changes in lake-effect snowfall have not been studied in Sweden, but for the Great Lakes of North America, studies have shown increasing trends (Burnett et al., 2003). However, the future of lake-effect snowfall is uncertain with divergent results and higher temperatures might change lake-effect snowfall to lake-effect rainfall events (Kunkel et al., 2002; Suriano and Leathers, 2015; Notaro et al., 2015). Some of the most intense snowfall events recorded in Sweden includes those in January 1985 close to Oskarshamn, in January 1998 close to Gävle, both on the Baltic coast, and in December 2012 south of Lake Vänern (http://www.smhi.se/kunskapsbanken/meteorologi/snokanoner-fran-havet-1.13740). All three events produced more than 70 cm of snow in less than 24 hours. The snowfall in Gävle continued for another day yielding a total of more than 130 cm with severe consequences including closing of train and road transport, closure of schools and cancelled treatments in hospital. This single event was estimated to cost about 50 MSEK (Hedman, 1999).

Future climate

The main pattern of changes in average precipitation over Europe consists of a dryer south and wetter north, due to a robust poleward shift of circulation patterns (Christensen et al., 2007; IPCC, 2014). Dynamic responses on such large scales, but also on smaller scales are important to understand as they are key in modulating the direct thermodynamic response to climate change (Pfahl et al., 2017).

IPCC states high confidence in a projected future increase in daily precipitation extremes for northern Europe in all seasons (IPCC, 2014). Indeed, it is one of the regions with the largest increases in heavy precipitation (Masson-Delmotte et al., 2018). This increase has been shown to be consistent over several regional model generations (Boberg et al., 2008; Boberg et al., 2009; Rajczak and Schär, 2017; Nikulin et al., 2011) as well as in high resolution global climate model projections (Kitoh and Endo, 2016). Olsson et al. (2018) investigated a set of nine regional climate models from the Euro-CORDEX ensemble with hourly precipitation data and found a significant increase of the ensemble median result of around 10% in all return values of extreme precipitation already from the coming decades, and exacerbated in the more distant future projections by 20% to 40% up to 2100, depending on the emission scenario (RCP4.5 and RCP8.5). The range between the minimum and maximum of the ensemble spans at most over 100% for short event durations and RCP8.5 towards 2100. Similar increase has been found for Sweden, using different methods including weather generators (Olsson and Foster, 2014; Chen et al., 2015; Larsen et al., 2009; Persson et al., 2015; Kjellström et al., 2014).

Although regional climate models provide higher quality daily precipitation data than the global climate models (Jacob et al., 2013), there are still issues with models of resolution of more than five to ten kilometres. For example, modelled extremes in sub-daily precipitation have shown severe underestimations for durations of less than about 12h for Sweden and elsewhere in Europe (Berg et al., 2019). The state-of-the-art of regional climate models is moving from scales of the order of ten kilometres toward an order of one kilometre, which means going from parameterized to mainly resolved convective motions. Several studies have shown benefits of the kilometre scale models, e.g. regarding the diurnal cycle of precipitation (Fosser et al., 2014; Prein et al., 2015; Kendon et al., 2017), which has long hampered the development of daily extremes in parameterized models (e.g. Trenberth et al., 2003). Studies have shown that the new model generation gives an improved representation of local storm scale dynamics (Kendon et al., 2014), with associated larger increases in higher precipitation extremes in future projections.

3.2 FLOODS

Background

Flooding can occur as a result of several different processes, but here we separate in a broad sense between snowmelt and rain induced flooding. Rising temperatures have a direct effect on snowmelt by moving the main discharge peak earlier in spring, and often reducing the peak due to a shorter snow accumulation season. A warmer climate also causes increased evapotranspiration and thereby lower mean discharge; thus lowering the probability of floods. However, an increased evapotranspiration can lead to adverse effects, such as dry soils becoming impervious which together with heavy rainfall responds with larger surface runoff than would normally occur. Such effects can increase the probability of flooding even without a change in precipitation.

Recent climate

The most severe floods in Scandinavia occur predominantly together with the main snowmelt season (Arheimer and Lindström, 2015; Wilson et al., 2010; Matti et al., 2017). The main observed trend of flood occurrence is of an earlier spring flow in snow-dominated catchments (Seneviratne et al., 2012; Wilson et al., 2010; Arheimer and Lindström, 2015; Matti et al., 2017). This is mainly caused by increasing temperatures, which shortens the snow season and thereby also shifts the flood regime from snowmelt to rainfall dominated (Matti et al., 2017). Rising temperature has been identified as the main driver of climate change in flood frequency and magnitude (Matti et al., 2017; Arheimer and Lindström, 2015), and changes in precipitation of secondary order (Wilson et al., 2010). Trends in extreme floods range from no significant trend due to large natural variability (Arheimer and Lindström, 2015), to significant increases (Matti et al., 2017).

Paleoclimatic studies have shown that warmer temperature offsets increases in precipitation to reduce flood peaks (Støren and Paasche, 2014) and that wet periods often concur with warm periods (Seftigen et al., 2017). It is therefore plausible that especially rainfall dominated catchments of Fennoscandia are unlikely to display significant trends in floods with the foreseen increases in temperature and precipitation.

The trend analyses are primarily based on non-regulated rivers. However, with a large hydropower industry, most Scandinavian rivers are strongly regulated, which makes trend analysis challenging if not impossible. Arheimer et al. (2017) showed that regulation of snow dominated rivers offsets climate change signals for snowmelt such that the hydrological regime remains intact.

Flooding due to cloudbursts can be severe in small regions due to the vast amounts of rainfall in short periods of only a few hours. Recent examples of very extreme events are the cloudbursts over Copenhagen in July 2011 and in Malmö/Copenhagen in August 2014. The event over Malmö is considered one of the most extreme cloudbursts ever recorded in Sweden, and had severe societal consequences (Hernebring et al., 2015).

Future climate

Hydrological modelling of extreme floods shows that there is no single response to a projected climate change for all catchments, but that catchment characteristics can cause distinctly different responses to the same change in climate (Teutschbein et al., 2015; Arheimer and Lindström, 2015; Matti et al., 2017). The main consistent changes are, as in observed trends, a change to earlier snowmelt induced streamflow peak and a general shift from a snowmelt to a rainfall dominated regime (Teutschbein et al., 2015; Arheimer and Lindström, 2015; Donnelly et al., 2017; Rojas et al., 2012; Roudier et al., 2015; Bergström et al., 2001; Olsson et al., 2011). Further identified changes are a decrease in snowmelt induced floods and an increase in autumn and winter floods as a consequence of more rainfall domination in the flood generation process (Teutschbein et al., 2015; Arheimer and Lindström, 2015; Vormoor et al., 2015; Olsson et al., 2011; Donnelly et al., 2017; Rojas et al., 2012; Roudier et al., 2015; Sjökvist et al., 2015). Extreme floods at 100 and 200-year return periods in historical climate show general increases over Sweden, except for snowmelt dominated parts in the north of Sweden and in north-west Svealand (Eklund et al., 2015; Sjökvist et al., 2015).

The future of cloudburst driven flash floods is uncertain, since there is a gap in scientific literature on this topic. The reasons are the dependence on reliable regional climate projections at sub-daily timescales (see section on precipitation), and that hydrological models constructed for climatological simulations at sub-daily time steps are only now becoming available (e.g. Olsson et al., 2017).

3.3 DROUGHTS

Background

Four types of drought are known: 1) meteorological drought, 2) hydrological drought, 3) agricultural drought, and 4) socioeconomic drought (not described here). Meteorological drought happens when dry weather patterns dominate an area. Hydrological drought occurs when low water supply becomes evident, especially in streams, reservoirs, and groundwater levels, usually after many months of meteorological drought. Agricultural drought occurs when crops become affected. Meteorological drought can begin and end rapidly, while hydrological drought takes much longer to develop and then recover.

Recent climate

Trends of drought in the observational record are difficult to find, due to uncertainties and sensitivities in detection methods. It is necessary to choose an indicator (a "proxy", e.g., precipitation, evapotranspiration, soil moisture or streamflow). That choice, together with time scale of observation can strongly affect the ranking of drought events (Stocker et al., 2013; Sheffield et al., 2009; Vidal et al., 2010). For example, Sheffield et al. (2012) showed that with a simplified model of potential evaporation, positive drought trends tend to be overestimated, while, when using more elaborated calculations based on available energy, humidity and wind speed the changes are less prominent. This is clearer in energy-limited regions such as northern Europe (Scandinavia), which now show a slight increase in trend in droughts rather than a significant increase that was shown in previous studies. Further investigation is needed on a regional scale since interpretation for the impact on the hydrological cycle and its extremes varies regionally.

For Northern Europe, a method that tries to overcome the aforementioned constraints (sensitivity on methods) is the use of tree-ring reconstruction from Fennoscandia in combination with SPEI (Standardized Precipitation and Evapotranspiration Index) to infer past local to regional drought/pluvial variability (Linderholm, 2005; Helama, 2009; Drobyshev et al., 2011; Seftigen et al., 2013; Seftigen et al., 2015). In particular, the SPEI is a frequently used drought indicator where discrepancies in the interpretation of changes over drought conditions can be easily moderated. The reconstruction allowed to identify major spatial patterns of moisture variability throughout Northern Europe, and to assess the robustness and stability of these patterns over the last millennium. A principal component analysis identified the major spatial moisture patterns in both the instrumental and reconstructed data, together explaining more than 50 % of the hydroclimatic variability in the region. These patterns are remarkably stable back to the mid thirteenth-century. The 500 mb pressure fields associated with these patterns shares some of the main features of the summer North Atlantic Oscillation (NAO), indicating an important role of the circulation on the moisture distribution in the region. The summer NAO is strongly associated with July–August climate variability over Europe, especially in northern regions. This association includes drought, where a positive summer NAO corresponds to dry conditions over much of northern Europe and wet conditions in southern Europe. An association between the summer NAO and a regional summer drought index from Sweden suggests that the northern European drought relationship holds back to 1700 (based on dendroclimatological reconstruction, Linderholm et al., 2009).

A separate analysis from the European Environmental Agency (Füssel et al., 2017), where a combination of three drought indicators - Standardised Precipitation Index (SPI, SPEI, and Reconnaissance Drought Index RDI) - was used to calculate trends in frequency and severity of meteorological droughts between 1950-2012 over Europe. This analysis showed a decrease in the frequency and severity of meteorological droughts over northern Europe and Sweden. In contrast, the severity and frequency of meteorological and hydrological droughts have increased in other parts of Europe, in particular in south-western and central Europe.

Future climate

The ability of past and recent coarse resolution climate models to represent basic drought conditions is limited. Although several studies have demonstrated a strong association between historical droughts and anomalies in sea surface temperature (SST), associated for example with El Niño or the Atlantic Multidecadal Oscillation, it remains unclear whether this association holds in projections of future climate, if climate models can reasonably represent basic drought properties, or whether models project increases in drought frequency and intensity.

For Scandinavia it is expected that drought will increase in frequency and severity in the future as a result of climate change, mainly as a consequence of decreases in regional precipitation but also because of increasing evaporation driven by global warming (Sheffield et al., 2012). During dry years, Sweden experiences water shortages that can cause major problems locally and regionally. It is mainly the eastern parts of Götaland and Svealand that are affected.

The European Environmental Agency (Fossel et al., 2017) shows that in snow-dominated regions (like Scandinavia), where droughts typically occur in winter, river flow droughts are projected to become less severe because a lower fraction of precipitation will fall as snow in warmer winters. In most of Europe, the projected decrease in summer precipitation, accompanied by rising temperatures which enhances evaporative demand, may lead to more frequent and intense summer droughts. Available studies (Roudier et al., 2015; Donnelly et al., 2017; Spinoni et al., 2018) project large increases in the frequency, duration and severity of meteorological and hydrological droughts in most of Europe over the 21st century, except for northern European regions. The greatest increase in drought conditions is projected for southern Europe, where it would increase competition between different water users, such as agriculture, industry, tourism and households.

To assess the impact of a 2°C global warming on hydrological extremes (floods, droughts magnitude and duration) in Europe, Roudier et al. (2015) used an ensemble of eleven high-resolution RCM outputs and three pan-European hydrological models. Results show that flood magnitudes could increase (for historical 10 years and 100 years return periods) significantly in most parts of Europe even for areas where the annual rainfall is expected to decrease in the future, like in Spain. However, in Fenno-Scandinavia the situation is more contrasted with (i) a large area that is expected to have less intense snowmelt floods, occurring earlier in spring except and (ii) the southern and coastal areas of Fenno-Scandinavia where an increase of rain-fed flood magnitude is projected. Future changes in hydrological drought magnitude and duration show contrasting patterns across Europe. Changes in droughts are not significant or show a reduction of droughts length and magnitude, especially in northern Fenno-Scandinavia and Western Russia where the reduction sign of the changes is also very robust. In parts of Norway, Sweden, Finland and western Russia future warming will see a reduction in both streamflow floods and droughts.

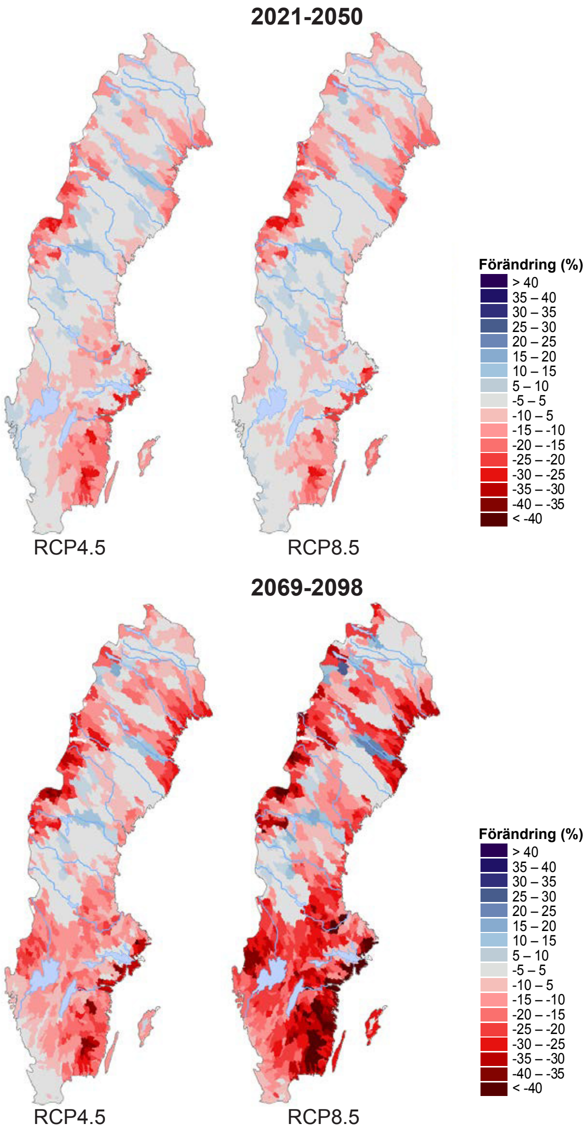


Figure 3.2: Relative change (%) in water availability for future scenarios relative to a historical period (1963-1992) for the middle (top) and end (bottom) of the century. From figure 3.24 in Eklund et al. 2015.

3.4 WIND AND STORMINESS

Background

In Fenno-Scandinavia and Europe large-scale windstorms are associated with mid-latitude cyclones (mid-latitude cyclones are also known as extratropical cyclones, meaning cyclones outside the tropical region), or lows ("lågtryck" in Swedish) as they are commonly referred to in everyday language. Windstorms are caused by strong pressure gradients associated with the deep low pressure at the centre of intense mid-latitude cyclones. The mid-latitude cyclones are linked to the polar front and gain their energy from the horizontal temperature difference across the frontal zone. The stronger the temperature gradient is, the more intensive a mid-latitude cyclone may become. The mid-latitude cyclones move with the large-scale atmospheric flow and may arrive to Sweden from any direction depending on the specific weather situation at hand, even though the westerly sector dominates because of the prevailing westerly winds. Typically the mid-latitude cyclones arriving in Sweden are formed in the North Atlantic region (Figure 3.3), in particular during the winter season (October-March) when most intense windstorms occur, hence these mid-latitude cyclones are often referred to as "winter storms".

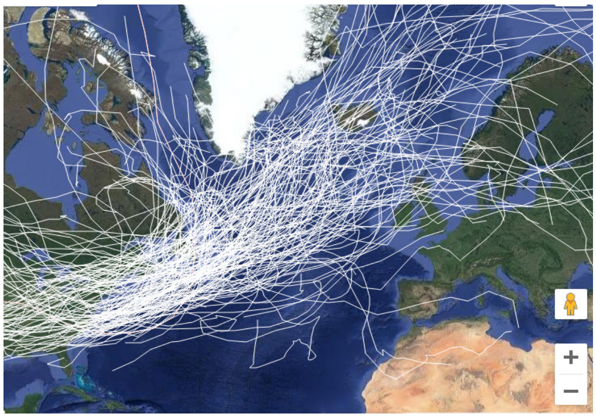


Figure 3.3: The 200 most intensive midlatitude cyclones in the North Atlantic winter season (December–January) during the period 1989/90 – 2007/8. Figure downloaded from http://www.met.rdg.ac.uk/~storms/ and reprinted with kind permission (Dacre et al., 2012).

Mid-latitude cyclones should not be mixed up with tropical cyclones that occur in the tropical north Atlantic (i.e. further to the south compared to the mid-latitude cyclones) and moves westward to frequently hit the Caribbean region, the Gulf of Mexico, and the east of the USA. A tropical cyclone gains its energy from the warm surface water of the tropical ocean. If it is intensive enough it becomes a hurricane. Sometimes their path recurve towards a more northwesterly one. Once moving in over land or outside the area of high enough surface water temperature they begin to decay. Almost 50% of the decaying tropical cyclones -- far from all being hurricanes -- reach the zone of mid-latitude upper air flow and undergo transformation to mid-latitude cyclones that move with the prevailing eastward flow and may thus reach Europe (Hart and Evans, 2001; Evans et al., 2017), Figure 3.4.

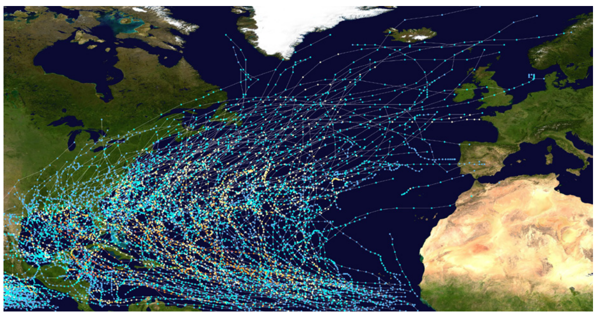


Figure 3.4: Tropical cyclones which formed worldwide from 1985 to 2005. The points show the locations of the storms at six-hourly intervals and use the color scheme shown to the right from the Saffir-Simpson Hurricane Scale. Downloaded (2018-09-20) and excerpted from https://en.wikipedia.org/wiki/Tropical_cyclone#/media/File:Global_tropical_cyclone_tracks-edit2.jpg.

Another important factor for the impact of mid-latitude cyclones and the damage they inflict is the tendency for intensive mid-latitude cyclones to cluster in time. This serial clustering of and the multiplicative effect on impacts has recently gained interest (e.g. Mailier et al., 2006; Vitolo et al., 2009; Hunter et al., 2016; Priestley et al., 2018). The processes resulting behind this clustering is linked to the large-scale atmospheric flow (e.g. Pinto et al., 2014; Franzke, 2013; Walz et al., 2018) and thus to the very active research on the large-scale dynamics of the northern hemisphere atmosphere.

While the pressure gradient of the mid-latitude cyclone determines the large scale wind speed and direction, other factors contribute to produce the regional-scale extreme winds that typically are responsible for the severe impacts of a windstorm. At the regional scale phenomena related to life-cycle evolution of the cyclone and its fronts are important (cf. Hewson and Neu, 2015; Earl et al., 2017; Clark and Gray, 2018). Another aspect is the static stability which influences the wind gustiness and thus the temporary maximum wind. At local to regional (ca 100 km) scale topographic steering and channeling is important, and surface friction induced by vegetation and land-use, as well as small-scale topography (10-100 km) is important at the very local (km) scale as it influences the wind gustiness. At the very local scale wind extremes are often associated with intensive local convective systems. These are dealt with in the section on tornadoes.

At the local to micro scale, which is the scale relevant for wind measurements, local vegetation and land-use conditions change, sometimes drastically, over the years that pass. This makes it difficult to use wind observations and wind speed measurements for long-term climatological studies. Instead, a commonly used method is to use horizontal pressure gradients derived from surface barometer readings to calculate the geostrophic wind. A number of other approaches are available to analyse various aspects of mid-latitude cyclone intensity and activity, collectively known as storminess.

Recent climate

Because long-term homogeneous and high quality observational records of wind conditions are very scarce, a range of alternative approaches are used to shed light on long-term variations and changes of the wind climate. A rich range of literature is available regarding mid-latitude cyclone activity, storminess and wind climate, and there are several comprehensive reviews of the scientific literature up to about 2013-2014. Focussing on global trends, IPCC AR5 (Hartmann et al. 2013; sect 2.6.4) concludes that there was no clear indication of long-term trends in cyclone frequency or intensity.

In their own words:

> »In summary, confidence in large scale changes in the intensity of extreme extratropical cyclones since 1900 is low. There is also low confidence for a clear trend in storminess proxies over the last century due to inconsistencies between studies or lack of long-term data in some parts of the world (particularly in the southern hemisphere). Likewise, confidence in trends in extreme winds is low, owing to quality and consistency issues with analysed data.«

Focussing on the European wind extremes, Hov et al. (2013, p. 46) conclude that:

> »In summary, there is some evidence that winter wind storms over North-western 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; ...«

Similarly, Füssel et al. (2017, p. 85)] states as key message that:

> »Storm location, frequency and intensity have shown considerable decadal variability over the past century, such that no significant long-term trends are apparent.«

In the second assessment of Baltic Regional Climate Change, BACC-II, Rutgersson et al. (2015) present a detailed review of the scientific literature up to about 2010. They point out that there is a strong link between large-scale forcing mechanisms, such as the North Atlantic Oscillation (NAO) and the wind climate. While they do not summarize the review into a succinct key message, the conclusion is that there was a strengthening of the large-scale forcing mechanisms from about 1960 to the mid 1990's, and thus the surface wind climate, but point out that this may be more related to multi-decadal variations than a consistent long-term change. This review was updated by Feser et al. (2015), who conclude that for Sweden (Scandinavia) there are as many studies showing an increasing trend as there are studies showing a decreasing trend, and almost as many showing no clear trend. However, when stratifying the studies on which type of data sources were used in the individual studies there is a clear difference between those based on observational data and those based on reanalysis data. Moreover, alternative reanalysis datasets may give different results (e.g. Befort et al., 2016). Most observational studies cover a substantial part of the 20th century and many extends back into the 19th century. Reanalysis data, on the other hand, typically extends back only to the 1950's or 1960's with a few notable exceptions. In their conclusions, Feser et al. (2015) stress that the trends crucially depends on which dataset and which time period is analysed and find that most studies based on centennial data sources stress (multi-)decadal variations. They also conclude that if only the last four to six decades are taken into account, many studies indicate an increase in storminess.

The previous paragraph summarised several reviews of the scientific literature up to about 2010 to 2013. However, recent findings using more up-to-date datasets and methods do modify this picture. First focussing on Sweden, since 2009 SMHI updates information on geostrophic winds on an annual basis (Wern and Bärring, 2009; Wern and Bärring, 2011). The web service (https://www.smhi.se/klimat/klimatet-da-och-nu/klimatindikatorer/klimatindikator-geostrofisk-vind-1.3971) provides information and data on mean geostrophic wind speed, maximum geostrophic wind speed and number of days when the geostrophic wind speed exceeds 25 m/s, as well as potential geostrophic wind power. Data for the two southern triangles (Figure 3.5a) extends back to 1901, the other triangles cover the period since 1940. By perusing the information presented in this web service the consistent picture emerges that there is no clear-cut indication of a trend in any of the four geostrophic wind measures. In some triangles and measures (e.g. number of occasions above 25 m/s in triangles 1 and 2, figure 3.5b) there was a peak in the early 20th century which results in an overall decreasing trend modulated by decadal variations. For the other triangles the data do not extend back to cover this period (e.g. Figure 3.5c).

The main reasons for focussing on geostrophic wind is that it provides a good description of the regional wind climate and, in particular, that it is possible to obtain long high-quality homogeneous time-series. On the other hand, it is somewhat difficult to relate the geostrophic wind to the actual wind experienced or observed. To bridge this gap Minola et al. (2016) present an analysis of homogenised time-series of monthly mean wind observations from 33 meteorological stations covering the period 1956-2013, also drawing on the geostrophic wind data for comparison and quality control purposes. Their overall conclusion is that with few exceptions there is a decreasing trend in the Swedish mean wind climate. This decreasing trend is less pronounced during winter, but more pronounced at coastal stations in southern Sweden. In a similar study, Laapas and Venalainen (2017) analysed monthly mean and maximum wind measurements from 39 Finnish stations covering the period 1959-2013 (144 stations in total when including shorter periods) and came to a similar conclusion about decreasing trends in both monthly mean and maximum wind speed. This largely decreasing trend in mean winds over Sweden and Finland is in line with a number of studies across the globe (cf. McVicar et al., 2012; and Minola et al., 2016; for further

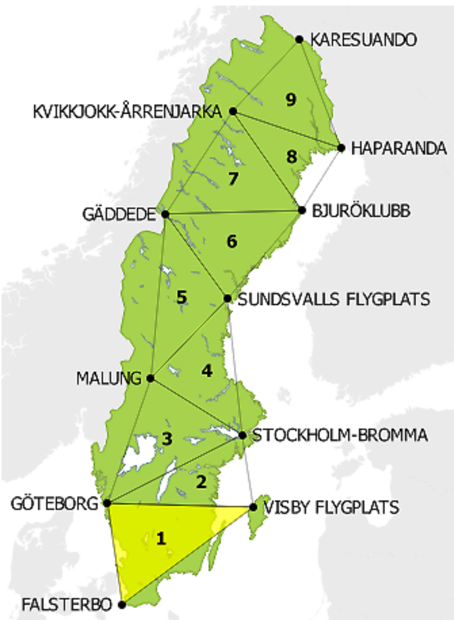


Figure 3.5: a) Geostrophic wind triangles for Sweden (source: SMHI);

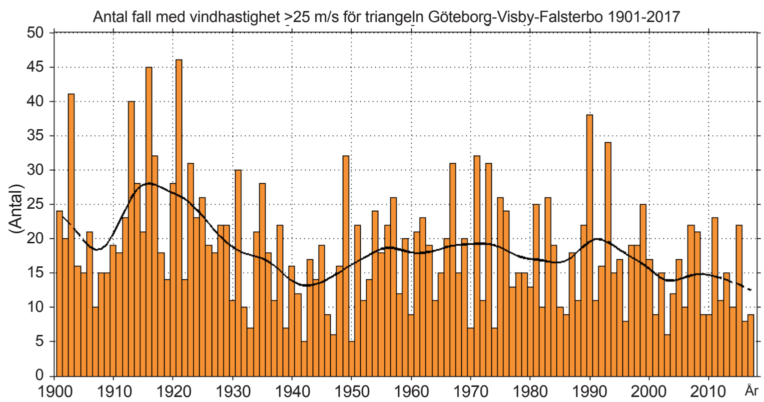


Figure 3.5: b) Annual number of occasions of geostrophic wind above 25 m/s in triangle 1, Falsterbo–Visby flygplats–Göteborg

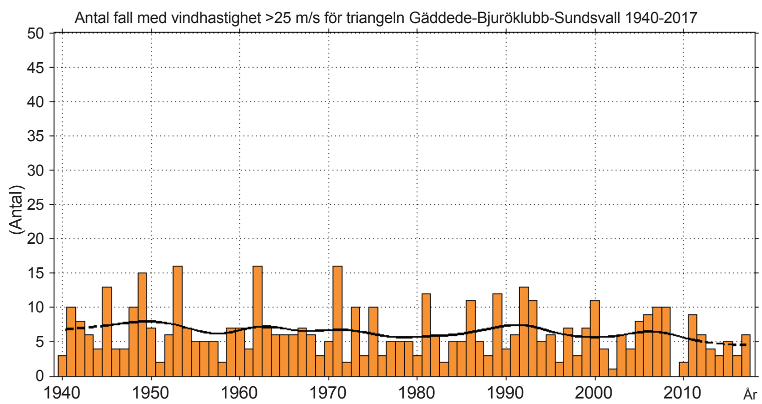


Figure 3.5 c) Annual number of occasions of geostrophic wind above 25 m/s in triangle 6, Gäddede–Bjuröklubb-Sundsvall.

references). Changes in land surface friction induced by anthropogenic land use changes has been identified as one of several plausible causes for this downward trend (e.g. Vautard et al. 2010), although a final conclusive understanding as to the reasons for remains to be established. Recently, Wu et al. (2018) provide a review of the literature and attempts at disentangling different factors in order to outline future research directions towards resolving this apparent contradiction in trends.

Currently, it is difficult to find a consolidated and well rounded general conclusion regarding recent and current large-scale wind variations and trends. In particular, there seems to be a discrepancy between the conclusions drawn from observational studies and those based on reanalysis datasets. In this context it is worth caution that the reanalysis datasets used in those studies are susceptible to several sources of observational inconsistencies and imitations in the observational system (cf. Box2.3 of Hartmann et al., 2013). Fortunately, substantially improved global and European-wide reanalysis datasets are currently being rolled out from the Copernicus Climate Change Service. To conclude this part by focussing on the Swedish wind climate, it is important to point out that there is no observational evidence for any long-term trend towards a more severe wind climate.

The previous paragraphs dealt with the large-scale wind climate closely related to mid-latitude cyclone activity, inferred from the geostrophic wind calculations and observed or measured at meteorological stations. The most severe wind extremes are however related to the regional processes which for Sweden seems to have received little focus in a climatological context. In an in-depth analysis for UK Earl et al. (2013) were able to attribute the occurrence of regional/local extreme winds to the respective regional features. In process oriented studies Earl et al. (2017), Clark and Gray (2018) make references to some of the recent intensive windstorms hitting Sweden, without any detailed studies focusing on Sweden.

Future climate

Given the fact that windstorms are one of the most damaging meteorological phenomena there is substantial interest in predicting the future evolution of windstorm frequency and intensity in the North Atlantic/European sector. There exist numerous studies drawing on both global and regional climate simulations, and those published before 2014 were reviewed by Feser et al. (2015). They conclude that that there is no common trend in the storm number across the different subregions analysed, but a clear indication of increased intensity. However, only a few of those studies (8 out of 82) focus on the Scandinavian/Baltic subregion, and a majority of those indicate fewer storms but an increasing intensity. In another re-view of the literature (Mölter et al., 2016) arrive at a simi-lar result but put more focus on the limited evidence re-garding northern and eastern Europe. Again assessing the results of partly the same scientific literature, but focussing on the larger North Atlantic and European region, Christensen et al. (2013) conclude in their assessment summary that the response of the North Atlantic storm track to global warming is more complex and less certain than for the corresponding features over the Pacific and in the southern hemisphere. While the North Atlantic storm track is a general feature of the large-scale atmospheric flow, it is a key factor influencing location, frequency and intensity of mid-latitude cyclones and thus indirectly extreme winds in northern Europe and Scandinavia.

Focussing on extremes and their impacts, IPCC (2014) finds that the projections suggest a small increase in extreme wind speed in central and northern Europe. Likewise, mainly assessing results from ensembles of regional climate scenarios Christensen et al. (2015) stress that in the Baltic Sea region projected wind changes are uncertain, but nevertheless found that the results point towards an increase in the annual maximum of daily mean wind speed expressed as 20 year return value. For daily maximum values the inter-model spread is larger than it is for daily mean wind speed. Other reviews (Hov et al., 2013; Füssel et al., 2017) focussing on the European scale are equally cautious in their conclusions. It is worth pointing out that these reviews and assessments are based on more or less the same body of scientific literature, which in turn draw on the same generation of climate models and available scenario ensembles.

Moving on to the more recent literature Christensen et al. (2013) point out model resolution as a key factor for representing mid-latitude cyclones, and also that the models' limitations in representation of some physical processes reduce the confidence in projections of future wind climate.

Haarsma et al. (2013) used an early very high-resolution version of the EC-EARTH global climate model (~25 km, which is enough to resolve tropical cyclones) to simulate six member ensemble time-slices of recent climate (2002-2006), and two future epochs (2030-2034 and 2094-2098) under the intermediate high RCP4.5 emission scenario. They found that the greenhouse warming increases the frequency of hurricane-force storms over Western Europe in the autumn (August-October). The majority of these storms originate as tropical cyclones, and they attribute this to the warmer sea-surface temperature of the Atlantic. Baatsen et al. (2015) carried out a deeper analysis of the same dataset to elucidate the dynamical features of the mid-latitude cyclones. They found that, as the warming increases in the future epochs, the mid-latitude cyclones become more frequent and transforms into a particularly intensive type having deep low pressure centre and strong winds in the mature stage of its lifetime.

It is however important to point out that these two studies use one model only forced by one emission scenario and a comparatively small ensemble of short simulated time periods. In a recent study Dekker et al. (2018) used a moderately high-resolution (~55km x 70km) reanalysis dataset (MERRA) covering the period 1979-2013 to analyse European cyclones with tropical origin and found that already today more than 50% of the cyclones follow the warm seclusion life-cycle and that the pressure minimum, i.e. their most intensive stage occur after reaching in over land. In a recent study of Euro-Atlantic winter storminess under 1.5°C and 2°C global warming scenarios, Barcikowska et al. (2018) compared results from the same global model at three different resolutions. They conclude that increasing resolution substantially decreased the model bias. Based on the high resolution version (~30 km) of their model results they found, in particular at warming levels above 1.5°C, a shift in the North Atlantic storm track towards northeast leading to an increase in wind extremes and storminess over Northern Europe and Scandinavia (see Figure 3.6). Using a multi-model ensemble of high-resolution simulations Li et al. (2018) analyse the atmospheric circulation and arrive at a similar conclusion of an eastward shift of the North Atlantic storm track that emerge at a temperature increase of 2°C.

Next, we move on to the few modelling studies more directly focussing on impacts. Karremann et al. (2014) used an ensemble of future projections based on two scenarios to analyse possible projected changes in return periods of serially clustered severe windstorms. They conclude that the projected return period for serially clustered windstorms above predefined damage levels decreases over most of Europe except the Mediterranean. Based on a subset of the CMIP5 ensemble of historic and RCP4.5 simulations Devis et al. (2018) calculated present day (1979-2005) and near future (2020-2049) wind power resources stratified into four groups, summer/winter and day/nights. For parts of Sweden they found increase in projected mean wind speed that is significant over some regions depending on which season and whether day or night. This climate change signal becomes stronger and more significant when considering the mean power output, mainly because the power output is a function of the wind speed cubed. Thus, a small change in frequency of

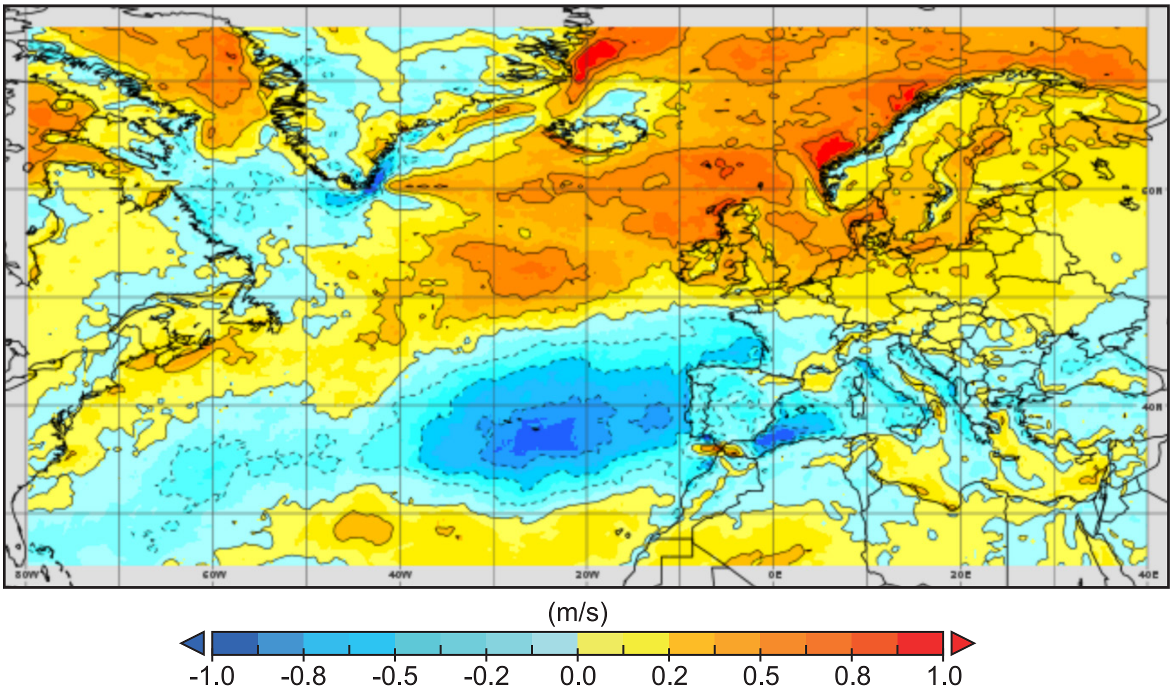


Figure 3.6: Difference between +2°C and 1.5°C ensemble experiments for winter (December-February) 95th daily wind percentiles (Barcikowska et al., 2018).

high wind speeds contribute to a linear change of the mean wind speed but has a stronger impact on the wind power. However, both these studies comparatively coarse resolution global models, which thus carry the same limitations as discussed above.

A different approach is to use regional climate models to downscale coarse resolution global data, either from reanalyses or from global climate models. Indeed, this is one of the most common approaches employed in the studies summarised in the reviews and assessments presented earlier. Using the state-of-the-art multi-model regional climate scenario ensembles under RCP8.5 at resolution of ~12.5 km, Kjellström et al. (2018) analysed the European regional climate change signal under 1.5°C and 2°C. They found that there is generally little consistency across the different ensemble members in the wind climate changes over Europe and over Fenno-Scandinavia, see Figure 3.7. Comparing the bottom panel of Figure 3.7 with Figure 3.6 reveals broad similarities.

3.5 LOCAL EXTREMES RELATED TO CONVECTIVE SYSTEMS - HAILSTORMS, THUNDERSTORMS, AND TORNADOES

Background

Intensive convective systems are typically associated with severe local weather, such as intensive precipitation, thunder and/or strong wind gusts. If the convective event is strong enough the system may result in local extreme conditions. In this chapter we will focus on local wind extremes, thunderstorms and hailstorms. Extreme local rainfall events and cloudbursts are treated in the section on Rainfall extremes.

Severe thunderstorms with large hail are associated with deep convection. Globally, there is a strong predominance of lightning over the continents relative to that over the oceans indicative of the stronger updrafts over land (Williams, 2005). In a comprehensive study of a large number of severe thunderstorms over central Europe, it was concluded that the occurrence of lightning is mainly a function of convective available potential energy (CAPE) and that it is more likely when the temperature of the equilibrium level drops below -10°C (Taszarek et al., 2017).

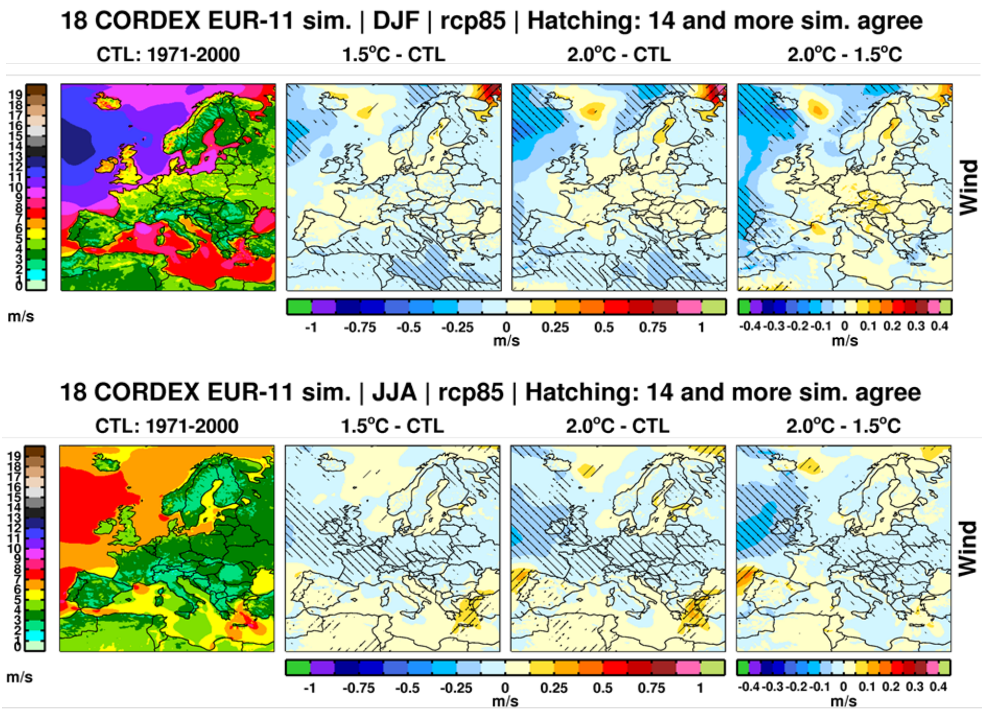


Figure 3.7: Ensemble mean winter (December-February) 10 m wind speed in the control period (top), its change at SWL1.5 (second column) and SWL2 (third column), and the difference between the change at SWL2 and SWL1.5 (rightmost column). Hatching in the climate change signal for wind speed represents areas where at least 14 of the 18 ensemble members agree on the sign of change. Cross-hatching indicates that there is agreement on the sign of change and that the signal-to-noise ratio is larger than 1. Hatching in the rightmost plots indicates that changes at SWL2 are larger than those at SWL1.5 in at least 14 of the models (top) same as a) but for the summer season, June-August (bottom).

The same study finds that the size of hail is mainly dependent on the deep layer shear in a moderate to high CAPE environment and that high moisture content of the boundary layer maximizes the probability of large hail. Lightning is not only dependent on the large-scale meteorological conditions but also on microphysical properties of the clouds that also involves aspects of aerosol content of the atmosphere (Price, 2013).

Tornadoes are associated with intensive convective cells (cumulonimbus clouds and thunderstorms), where updraft and downdraft have a tendency towards helical movement [corkscrew movement]. While the exact process for producing tornadoes are not know in full detail (Davies-Jones, 2015), the helical movement can under certain conditions be concentrated to a limited region that extends towards the surface below the cloud. The proverbial (emblematic) tornado is the devastating weather phenomenon in the Midwest USA capable of totally destroying everything in its way. The severity of these tornados is an effect of the warm and moist air from the Mexican Gulf meeting the hot and dry air inland, creating deep supercell convection that connects to strong upper air flow (jet streams). In Europe and Fenno-Scandinavia the same specific conditions do not coincide to create convective activity of the same magnitude as in North America. Consequently, European tornadoes rarely reach the same devastating intensity as in North America. In Scandinavia the size near the ground is typically 10-100 m and in North America even exceeding 1000 m.

Recent climate

Even if convective cells and thunderstorms are less intense in Europe than in North America, they frequently occur and give rise to hail and lightning, sometimes resulting in severe impacts. Trends in hail frequencies show different signs in different parts of Europe. Statistical significance is often lacking due to insufficient data and in some regions changes have been attributed to changes in reporting procedures or artificial cloud seeding programs (Punge and Kunz, 2016). For lightning strikes remote sensing detection systems have been used for the last decades allowing for characterising spatial and temporal variability, although improvements in detection capabilities over time prevents studies of long term trends (Yair, 2018). Due to the lack of data, methods assessing changes in large-scale atmospheric conditions favorable of deep convection have been put forward as a proxy for hail occurrence. In their review Punge and Kunz (2016) conclude that such studies suggests that there has been some trends of locally or regionally increasing hail intensity and/or frequency in Europe. Also for Sweden studies are lacking with the exception of an early, very comprehensive report based on 50 years of station data by Hamberg (1917). In that work it is noted that large hailstones (> 20 mm diameter) were only reported a few times a year in the entire country. The largest hailstone ever reported in Sweden (July 1953) had a diameter of 80 mm and a mass of 200 g. Hailstones of such very large size have been reported over a majority of the European countries with a maximum in central Europe (Punge and Kunz, 2016). A clear seasonality of heavy thunderstorms result in the most intense hail events and most frequent lightning strikes in summer (Holt et al., 2001; Mäkelä et al., 2014).

The last several decades have seen a growing scientific interest in European tornados and the need to compile databases of tornado events. The European Severe Storms Laboratory, ESSL (www.essl.org) has emerged as an unofficial European focal point for collection and quality control of reports on tornadoes and other local severe weather phenomena, as well as related research and training (Groenemeijer et al., 2017). Drawing on the work of this organisation, Antonescu et al. (2016) present a comprehensive review of European records of historic tornado events. The information ultimately comes from damage accounts or eyewitnesses often reported in newspaper articles. Not surprisingly given the fact that tornadoes are very local phenomena, Groenemeijer et al. (2017) show that in Europe (not least Sweden) there is as strong correlation between tornado incidence and population density. Antonescu et al. (2016) and Groenemeijer et al. (2017) show that there seems to be a clear increase of tornado incidence over the last several decades, but attributes this primarily to changes in reporting rather than a clear indication of a climate change signal. And Groenemeijer et al. (2017) conclude that tornadoes are probably still underreported. Antonescu et al. (2016) note that Sweden has a long record of tornado observations based on various early compilations and more recently the record of reported events that SMHI maintains (www.smhi.se/kunskapsbanken/meteorologi/tromber-1.3875). Swedish tornadoes rarely reach above EF2 intensity (111–135 mph, "Considerable damage" according to "Enhanced Fujita scale" for tornadoes). From the (Antonescu et al., 2016) review of Swedish sources it is evident that climatological analyses of the existing observations on tornadoes in Sweden and their impact are missing or out-of-date.

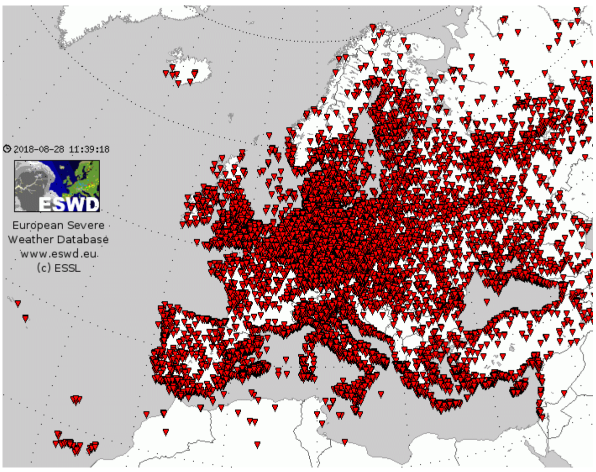


Figure 3.8: Map showing all tornado events recorded in the ESSL database up to 2018-08-28.

Future climate

Increasing temperatures and moisture content of the atmosphere is favorable of deep convection implying that hailstorms, thunderstorms and tornadoes may become more frequent and/or intense in a warmer climate on a general level (Yair, 2018). The regional response, however, is less certain due to uncertainties in changes of large-scale atmospheric circulation and in local-scale warming conditions. A general limitation in assessing changes in these phenomenons is the capabilities of climate models to represent them in a realistic way. Recent development of high-resolution regional climate models have shown significant differences relative to coarser scale models for precipitation related to convective precipitation (Kendon et al., 2014) but results from such experiments are still lacking for most areas. Warmer temperatures over continents, and thereby deeper convective clouds, would favor more lightning in the future. At the same time, however, changes in microphysics with a smaller fraction of ice particles in the clouds would favor less lightning (Finney et al., 2018). Dependent on how conditions favorable of lightning are determined in climate models either increases or decreases can be obtained for a future warmer climate (Murray, 2018).

This issue of ice particles in clouds is subject to current research. Due to the small scale nature of tornadoes, they cannot be directly simulated on a routine basis in current climate models. Some particularly strong events have drawn specific interest for recent research. The EF3 (136–165 mph, "Severe damage") tornado hitting southern Italy on 28 November 2012 has been used in detailed simulation studies (Miglietta et al., 2017; Miglietta et al., 2017), and similarly two EF3 tornadoes hitting eastern Greece were analysed using a high-resolution model (Avgoustoglou et al., 2018; Mylonas et al., 2018). The F1 tornado hitting Hamburg, Germany, 7 June 2016 was analysed using radar data and model simulations (Hoffmann et al., 2018).

3.6 ICE STORMS, FREEZING RAIN

Background

An ice storm is characterised by freezing rain accumulating a significant ice layer on exposed surfaces, thus damaging trees and utilities infrastructure as well as causing traffic problems due to slippery road conditions. The general condition conducive for creating freezing rain is cold surface conditions with a surface air layer below freezing temperature and warmer and moist air above where the precipitation is generated. The precipitation reaches the cold surface air layer as rain that becomes super cooled when passing though the cold surface air, whereupon they freeze to ice immediately when hitting a surface. For a freezing rain episode to be designated as an ice storm an ice layer of significant thickness has to accumulate thus causing severe damage and traffic problems. In the USA the minimum thickness is usually taken to exceed ¼ inch or 6.4 mm (https://forecast.weather.gov/glossary.php?letter=i, accessed 2019-03-27), but notable ice storm events involve substantially thicker layers, and in the most disastrous events the ice layer approach or even exceed 100 mm thickness. In Sweden, SMHI does not have a specific definition for ice storms, but issue a level 2 severe weather watch when the forecast indicates at least 3 mm of frozen rain in 6 hours. If less freezing rain or drizzle is forecasted, or the ground surface is below freezing temperature, a level 1 watch can be issued without any predefined limits in place.

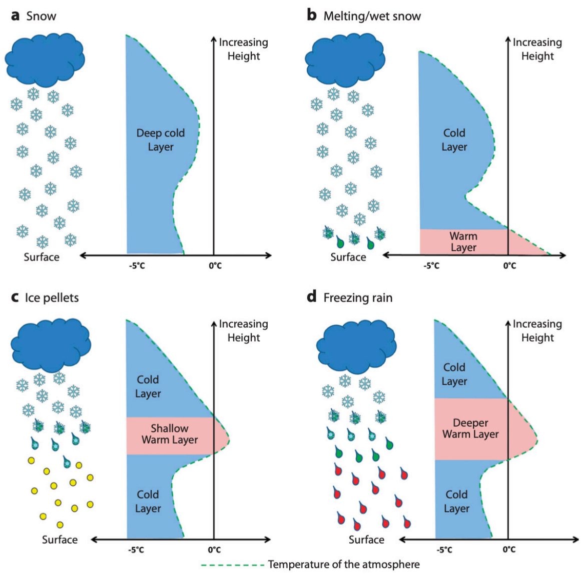


Figure 3.9: Sketch of vertical temperature profiles resulting in different types of precipitation. Upper left: Air temperature of the whole air column is below freezing point results in snow. Upper right: A warm surface layer that partly melts the snowflakes results in wet snow on the ground. Lower left: A shallow warm layer aloft that partly melt the falling snow that then transformed to ice pellets when passing through the colder surface layer. Lower right: A thicker warm air layer aloft will fully melt the snow to rain, whereupon the raindrops becomes super cooled when falling through the cold surface layer, and immediately freeze when hitting a surface. The illustration is reproduced with permission from Forbes et al. (2014).

Recent climate

Since a devastating ice storm in eastern Canada 1998 the risk for a similar event in Sweden has been considered and is a prominent example in the Swedish risk assessment and contingency planning discourse (Fischer 2001; MSB 2010; Franzén 2004; https://demo.krisinformation.se/detta-kan-handa/extremt-vader-och-naturolyckor/vinterovader/isstormar (accessed 2018-12-11); Riksrevisionen 2007).

However, in Sweden there are no clear-cut examples of ice storms as per the American definition. An event on 23-24 October 1921 is often referred to as a Swedish ice storm that caused severe damage to vegetation and the infrastructure of the time in north Götaland and south Svealand. But a closer analysis of the available records show that it was not a proper ice storm produced by freezing rain, but rather wet snow that subsequently froze and caused widespread damage of the same kind as is typical for an ice storm (www.smhi.se/kunskapsbanken/meteorologi/tidiga-snofall-i-sverige-1.32935, accessed 2018-12-11; Lindström et al., 2001). Anecdotal evidence exists of an earlier more localized event sometime in late 19th century but it has not been possible to establish the exact date more precisely (Karlsson and Karlsson, 2003).

In response to a request from Riksrevisionen (2007), SMHI outlined the meteorological factors why ice storms are much less frequent and severe in south Sweden compared to in North America (SMHI, 2007).
The main factors listed are:

- Stronger horizontal temperature gradients in Canada compared to Sweden and north Europe.
- Eastern Canada is located in proximity to the large pool of very cold air in north and central Canada. In Sweden the corresponding cold air pool over Siberia and the Arctic only temporarily reach the region.
- The Rocky Mountains prevent most of the lows coming in from the Pacific Ocean region. But the few that deve lop to reach east Canada can grow stronger.
- The lows over east Canada generally move slower due to weaker winds aloft.

While the risk for ice storms may be lower in Europe, a recent devastating example occurred in Slovenia in February 2014 (Forbes et al., 2014; Matko et al., 2017; Nagel et al., 2016; Nagel et al., 2017; de Groot et al., 2018).

Broadening the perspective to less severe events, at the European scale some attempts have been made for developing freezing rain climatologies from meteorological stations for the rather short period 1995-1998 (Carriere et al., 2000), or by developing a method for post-processing of global ERA-Interim reanalysis data (Kämäräinen et al., 2017), or more indirectly, by focusing on forest damage impact in a central European region (Nagel et al., 2016). In Sweden severe freezing rain events are uncommon. During the period 2001-2017 only one of more than 100 issued icing and freezing rain watches was a level 2 event, on 19 December 2017, for mid and north Norrland (SMHI, 2017). Furthermore, Eriksson (2001) analysed a case study of road slipperiness caused by rain falling on cold surfaces.

Substantial investigations using numerical weather models have been carried out for icing on wind turbines in Sweden (Bergström et al., 2013) and in Finland (Hämäläinen and Niemela, 2017), and in Switzerland for general construction purposes (Grünewald et al., 2012). It appears that for Sweden and Europe a consolidated climatology of severe icing events, whether of ice storms proper only or including less intensive events, has yet to be compiled, cf. North American studies by Call (2010) and Mullens and McPherson (2017) and studies covering China (Wang et al., 2014). In a pan-Arctic study Groisman et al. (2016) of recent changes in number of freezing rain and freezing drizzle events, data for Sweden (and Finland) is missing.

Future climate

In recent years there has been substantial advances in sophisticated cloud microphysics parameterisations to represent freezing rain into numerical weather prediction models (e.g. Stewart et al., 2015; Ikeda et al., 2017; Thompson et al., 2017; Barszcz et al., 2018). But these micro-physics schemes are expensive with respect to computing resources and have yet to be adapted for incorporation into state-of-the-art high-resolution convective permitting climate models to allow extended and/or multiple scenario simulations; an initial proof of concept was made by Liu et al. (2017). Meanwhile, Klima and Morgan (2015) report on a "simple thought experiment" using vertical temperature profiles and plausible future temperature regimes to explore future scenarios for North America. And a recent operational version of the Canadian regional model, CRCM, has been used to produce scenarios of freezing rain and ice storms for Canada and North America (Cheng et al., 2011; Bresson et al., 2017; Jeong et al., 2018). Awaiting such sophisticated high-resolution simulations, Kämäräinen et al. (2018) applied the same procedure (Kämäräinen et al., 2017) to ERA-Interim in a study based on seven EURO-CORDEX RCM-GCM pairs. Their conclusion is that after bias-adjustment the RCMs show a northward shift in the occurrence maximum of freezing rain toward the future. In northern Europe, the seasonality of freezing rain is projected to change in such a way that the two present day maxima in early spring and late fall merge in midwinter, and in central Europe, the freezing rain decreases in all months. For Sweden the multi-model composite indicates a significant decrease in southern Sweden and a significant increase in northern Sweden.

3.7 HEAT WAVES AND COLD SPELLS/SNAPS

Background

It is ambiguous what a heat wave or a cold spell actually is, and several definitions are possible. The simplest is to define a heatwave or a cold spell as a period with consecutive days with temperature above or below a certain th-reshold. This could be based on daily average temperatu-re or daily maximum or minimum temperatures. The number of consecutive days should usually be at least three to be qualified as a heatwave or cold spell. The thres-hold based definition is specific for a region. Which abso-lute temperatures are considered extreme depends on the average climate; what is considered extreme in one region could be seen as normal in another (Lass et al., 2011). This problem can be avoided by percentile-based definitions (e.g. Alexander et al. (2006)). This gives a statistically clear definition. In later years more refined indices are developed that are statistically robust, easier to compare across regions and also takes into account the magnitude of a heatwave or a cold spell (rather than just the length), such as the warm spell duration index (WSDI) and the heat wave magnitude index (HWMI) (e.g. Russo et al., 2014). Similarly, for cold spells, the cold spell duration index
(CSDI) has been complemented by an index for severity

for instance by accumulating negative deviations in minimum temperatures (Lhotka and Kysely, 2014).

Heat waves and cold spells are usually associated with so called blockings, large-scale atmospheric anticyclonic circulation patterns (Xoplaki et al., 2003; Meehl and Tebaldi, 2004; Cassou et al., 2005; Della-Marta et al., 2007). In summer, such blockings produce subsidence, clear skies, light winds and prolonged warm conditions at the surface (Kunkel et al., 1996; Palecki et al., 2001; Xoplaki et al., 2003; Meehl and Tebaldi, 2004). Contrastingly, for winter conditions the clear skies lead to cold conditions unless sufficient moisture is present in the lowermost atmosphere to create boundary-layer stratus or stratocumulus cloud decks. Long-term changes in the persistence of blockings are still poorly understood (Hartmann et al., 2013). The temperature response at the surface to the summertime blocking situation can be enhanced by a deficit of soil moisture. With a deficit in moisture, evapotranspiration is suppressed and evaporative cooling is reduced (Hartmann, 1994; Lakshmi et al., 2004; Ferranti and Viterbo, 2006; Seneviratne et al., 2006). Such moisture deficit could be a result of the blocking itself, but could also be a result of previous dry conditions. This amplification of soil moisture–temperature feedbacks is suggested to have partly enhanced the duration of extreme summer heat waves in South-Eastern Europe during the latter part of the 20th century (Hirschi et al., 2011). In winter, a parallel enhancement of the temperature response to the blocking is related to snow and ice covering the surface and thereby isolating it from the lower atmosphere. This leads to a dramatic decrease in heat fluxes to the atmosphere leading to very low temperatures.

Recent climate

A consequence of the ongoing general global warming trend is that the number and/or length of heat waves increases in most parts of the world (Hegerl et al., 2007; Seneviratne et al., 2010; Hartmann et al., 2013); even though the increase is not uniform as the temperature increase is different in different parts of the world. For Europe IPCC states that with high confidence it is likely that warm days, warm nights and heat waves have increased since the middle of the 20th century (Hartmann et al., 2013) and that cold days and cold nights likely have decreased. Globally about 75% of the moderate daily hot extremes over land are estimated to be attributable to warming (Fischer and Knutti, 2015).

Since 1880 the length of heat waves in western Europe has doubled and the frequency of hot days has almost tripled. Daily summer maximum temperature has increased 1.7 °C from 1880 to 2005 in Scandinavia (Della- Marta et al., 2007). For large parts of the Arctic, including Scandinavia, the number and intensity of cold spells in winter have been found to decrease over the time period 1979-2013 (Matthes et al., 2016).

During the last 200 years three stages of change in extremes can be recognized in Europe: decreasing warm extremes up to the late 19th century; decreasing cold extremes since then and increasing warm extremes since 1961 (Yan et al., 2002). Since 1961 there is a pronounced increase in warm extremes in most sites studied, including Fennoscandia (Yan et al., 2002; Klein Tank and Können, 2003; Smid et al., 2019).

It is a challenge to associate a single extreme event with the ongoing climate change. Weather patterns do not form by climate change itself, and could occur even in an unchanged climate because of natural variations. Therefore it is challenging to disentangle the natural variability part and the anthropogenic part of a heatwave to attribute a specific heatwave to climate change is sometime controversial (Dole et al., 2011; Rahmstorf and Coumou, 2011). The event itself may be natural, but climate change can change the probability of extreme events (Otto et al., 2012). However recently, attribution of extreme events became a growing field of science. Methods for local attribution, involving climate models, have been further developed and quasi-operational services for event attribution are on the way to become established.

A background trend of increasing temperature increases the probability of heat waves and decreases that of cold spells. For example it is estimated that the probability of a heat wave like the one in 2003 in Europe has more than doubled because of anthropogenic influences (Seneviratne et al., 2012) and that the heatwave in Australia in 2013 could not be explained by natural causes only (Lewis and Karoly, 2013). Similarly, it is challenging to assess to what part the decrease or absence of cold spells over the past decades is due to natural variability or anthropogenic causes. However, Cattiaux et al. (2010) concludes that the severe cold winter of 2009/2010 was warmer than expected from analysis of the large-scale atmospheric circulation of that winter (Cattiaux et al., 2010).

Future climate

As the climate continues to warm in the future it is expected that warm temperature extremes will become more common on the global scale and that the magnitude of the changes increases with increasing anthropogenic forcing (Kharin et al., 2007; Sterl et al., 2008; Caesar and Lowe, 2012; Orlowsky and Seneviratne, 2012; Sillmann et al., 2013; Collins et al., 2013; Smid et al., 2019). Contrastingly, extremes associated with cold temperatures are projected to decrease and it is notable that some of the largest changes in cold extremes are projected at high latitudes (Collins et al., 2013). Regional assessments agree with global assessments in an overall sense; however, the uncertainty is larger for regions than for the continental/global scale. An analysis of CMIP data shows that climate models are able to reproduce present day temperature extremes (in terms of 20-year return periods) reasonably well; usually within a few degrees Celsius in most parts of the earth (Kharin et al., 2007; Kharin et al., 2013). CMIP3 and CMIP5 models perform about equally well, but with smaller model spread in CMIP5 (Flato et al., 2013). There is a tendency in CMIP3 simulations to overestimate the observed warming of warm extremes and underestimate the warming of cold extremes. This is less obvious in CMIP5 and needs to be studied more (Flato et al., 2013). The EURO-CORDEX regional climate model ensemble tends to overestimate the 90th percentile of summer temperature in southern and central Europe and underestimate it in Scandinavia. This also means that the persistence of heat waves is overestimated (underestimated) in southern and central Europe (Scandinavia), but the spread between models is large (Vautard et al., 2013).

In terms of absolute values, a 1-in-20 year warm temperature event (i.e. with the likelihood of happening once in 20 years) is globally projected to be 1-3°C warmer by the middle of the 21st century and 2-5°C warmer by the end of the century, a range of emission scenarios and models. Warm temperature extremes that in the present climate occur every 20 years will by the end of the century likely occur every second year, with the exception of high latitudes at the northern hemisphere where they are projected to occur every 5 years (Seneviratne et al., 2012; Collins et al., 2013). Contrastingly, current 20-year minimum temperature events are projected to become exceedingly rare, with return periods likely increasing to more than 100 years in almost all locations under RCP8.5 (Collins et al., 2013). The probability of a hot extreme at 2°C warming is almost double that at 1.5°C and more than five times higher than for present-day (Fischer and Knutti, 2015). Regionally the change in extremes may exceed global increases by far (Clark et al., 2010; Diffenbaugh and Ashfaq, 2010).

For Europe, an ensemble of regional climate models (RCM) project increase in amplitude, frequency and duration of heat waves, especially in southern Europe (Fischer and Schär, 2010). Another RCM ensemble concluded that the number of days above 30°C in regions like France and Hungary in the future will be similar as currently in regions like Spain and Sicily (Beniston et al., 2007).

Nikulin et al. (2011) show that the summer maximum temperature with a period of 20 years between 1971-2000, may in the end of the century occur every year in southern Europe and every 3-4 years in northern Europe while wintertime minimum temperatures may become rare and only occur every century or less (Nikulin et al., 2011). In a study with 10 RCMs, Russo et al. (2015) show that the probability of a European heat wave like the one in 2003 will increase in the future so that it may occur at least once in a 30 year period. They also show that the probability of a major European heat wave within the coming decades is larger in RCP8.5 than in RCP4.5 although the difference in projected global temperature change is small between the scenarios in the same period. That the change in heat wave frequency is not proportional to global temperature change is also shown by Dosio et al. (2018): compared to a 1.5°C warmer world the frequency of extreme heat waves is doubled in a 2°C warmer world.

It is indeed a natural consequence of a warming climate that heat waves become more frequent. It is, however, not certain that maximum temperatures (on which heat waves are defined) change in the same way as mean temperatures. In many regions hot extremes are reported to increase more than the mean temperature (Seneviratne et al., 2012; Collins et al., 2013; Fischer and Knutti, 2015; Schleussner et al., 2016). In statistical terms this means that the probability distribution not only moves towards higher temperature, but also gets a new wider shape. For European summer several studies conclude that there has been a recent increase in variability, and that variability will be amplified by global warming (e.g. Schär et al., 2004; Fischer and Schär, 2010; Barriopedro et al., 2011). Especially central and eastern Europe is a region where temperature extremes are projected to increase more than the corresponding mean temperature as a result of change variability (Schär et al., 2004; Clark et al., 2006; Kjellström et al., 2007; Vidale et al., 2007; Fischer and Schär, 2009; Fischer and Schär, 2010; Nikulin et al., 2011; Fischer et al., 2012; Vautard et al., 2014). The main reason for the wider probability distribution is the drying of the soil in the region. Lack of soil moisture reduces latent cooling and amplifies surface temperature (Seneviratne et al., 2012; Fischer and Schär, 2010). In Scandinavia local summer time maximum temperature is projected to increase in about the same way as the corresponding mean temperature regardless of scenario (Strandberg et al., 2015). For wintertime conditions, in areas where snow and ice exist in today's climate, it is common instead with a narrowing of the probability distribution for temperatures in a future warmer climate. In this situation, the cold extremes change much more than the average temperature and/or the warm extremes (Kjellström, 2004; Kjellström et al., 2007).

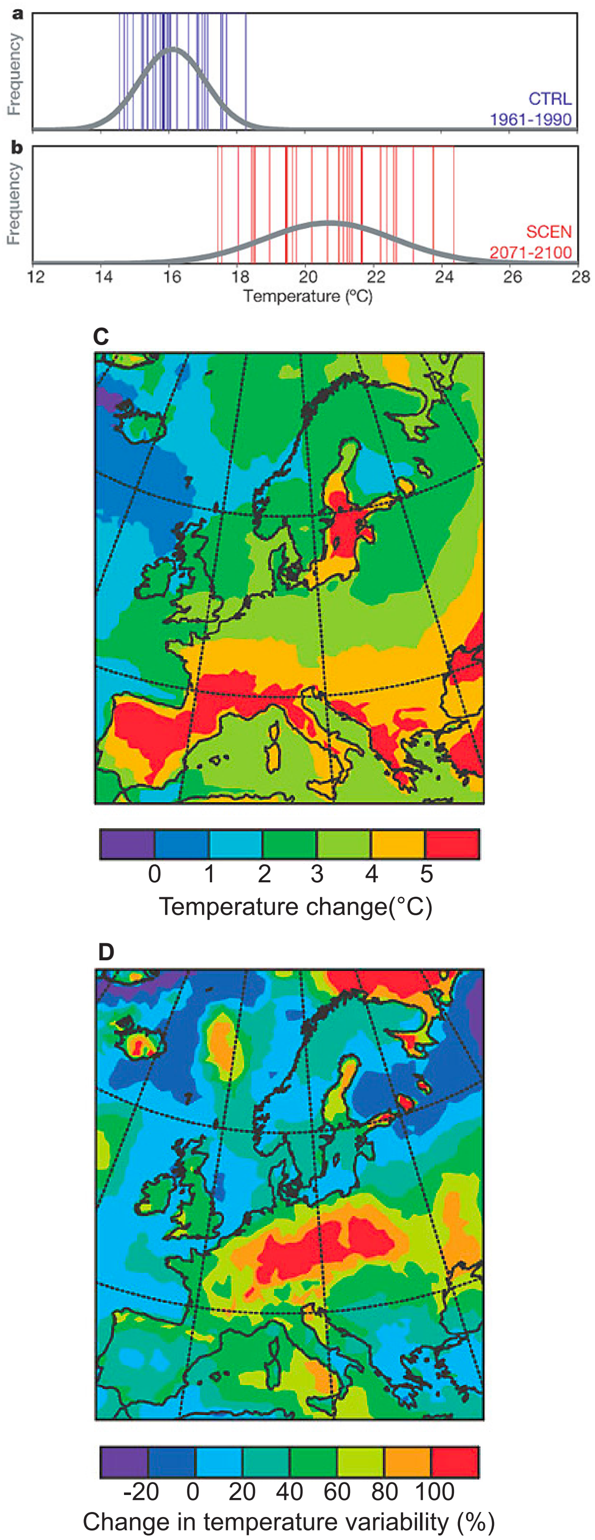


Figure 3.10: Results from an RCM climate change scenario representing current (CTRL 1961–90) and future (SCEN 2071–2100) conditions. a, b, Statistical distribution of summer temperatures at a grid point in northern Switzerland for CTRL and SCEN, respectively. c, Associated temperature change (SCEN–CTRL, 8C). d, Change in variability expressed as relative change in standard deviation of JJA means ((SCEN–CTRL)/CTRL, %). From Schär (2004).

Urban heat islands

As pointed out by e.g. Fischer et al. (2012) the heat stress may be different between urban and rural areas. The increase in temperature often seen over urban areas is called the Urban Heat Island (UHI) (Oke, 1982; Grimmond, 2007). There are several factors contributing to the increase in temperature over cities, the most important being caused by the urban terrain and its characteristics: lower albedo, higher heat capacity, limited green areas and anthropogenic heat sources. During day-time, hard impervious surfaces within a city reduce the cooling evapotranspiration in comparison to surrounding countryside and emit long-wave radiation, increasing the radiant temperature experienced by people (Thorsson et al., 2014). Also, a higher heat capacity allow materials in the built environment to store heat during day-time and release it during night time, causing a slower and smaller drop in temperature. The UHI increase the temperature over the whole day, but is usually strongest during night-time, raising the night-time minimum temperature, which has been linked epidemiologically with excess mortality (Luber and McGeehin, 2008). A few potential synergistic interactions between heat-waves and UHI are identified by Li and Bou-Zeid (2013).

Since cities in general have less vegetation and less surface moisture than the rural surroundings the ability of evaporative cooling is less. Another factor is that at high pressure systems with low wind speeds UHI is expected to increase due to the reduced advective cooling by low-temperature air from surrounding areas.

Also potential negative feedback mechanisms have been identified. For coastal cities a negative feedback mechanism could be caused by increased sea-breeze during heat-waves, drawing in cooler air from the sea (Lebassi et al., 2009; Lebassi-Habtezion et al., 2011). Another future negative feedback has been reported by Oleson et al. (2011), who found that an expected increased downward long-wave radiation, caused by increasing amounts of greenhouse gases, warms rural areas more than urban areas at night. The reason for the different responses is that the larger heat-capacity of urban areas buffers the increase in the UHI.

Many cities try to adapt to or mitigate the increased heat stress caused by the UHI. An example of a strategy for this is an increase of urban vegetation or reflective materials on roofs and pavements. Vegetation may restore moisture availability in urban areas, thereby reducing the increase in UHI during heat-waves. A limiting factor for the cooling effect of urban vegetation at mid-latitudes is the availability to water during during hot periods (Suter et al., 2017). Even though the temperature reduction that can be achieved is small on average, the effect on daily maximum temperature expected to be larger and can have a significant influence on the health impacts (Kovats and Hajat, 2008).

»Climate change could affect our society through impacts on a number of different social, cultural, and natural resources. For example, climate change could affect human health, infrastructure, and transportation systems, as well as energy, food, and water supplies.« (US EPA)

4. SOCIETAL IMPACTS OF CLIMATE EXTREMES

The impacts of weather and climate extremes are largely determined by exposure and vulnerability. Exposure refers to the presence of human and ecosystem assets and activities, which is a prerequisite for any impact, whereas vulnerability refers to the predisposition to be adversely affected. For a climate extreme to have a negative impact there must be both exposure and vulnerability. The interactions among weather or climate extremes, exposure and vulnerability are highly complex and involve also non-climatic factors (Handmer et al., 2012).

Knowledge of the impact of climate extreme conditions today and in possible future climates is necessary to determine the ambition of adaptation measures and to judge the consequences of climate change mitigation target levels, i.e. the 2°C of global mean warming goal.

The impacts of climate change on societal sectors and activities were discussed for Sweden in Holgersson et al. (2007). A summary, together with updates, were reported in MSB (2012). A further updated overview over societal impacts was published in SMHI (2014), which was provided by a governmental commission ("regeringsuppdrag", "kontrollstation 2015") on climate change adaptation.

In the above reports no distinction has been made between impacts associated (mainly) with changes in average climate and those impacts associated (mainly) with climate extremes. Therefore, the main objective of this chapter is to highlight societal impacts specifically and significantly associated with climate extremes, and to provide an updated status on these impacts. We will generally follow the sectoral division used in SMHI (2014), albeit omitting some items for which extremes have only a minor and/or unclear impact. The contents of this section are mainly based on (i) a summary of parts in SMHI (2014) related to climate extremes and (ii) relevant scientific publications that have been published since SMHI (2014) (also some earlier references not mentioned in SMHI (2014) have been added). The section is thus not intended to be a complete review of literature on climate change impacts in Sweden but an overview of the main impacts supported by selected papers and reports.

4.1 WATER SUPPLY AND SEWERAGE

Concerning water supply, the impact of climate change on drinking water supply was thoroughly investigated in the governmental commission Dricksvattenutredningen (The Drinking Water Investigation; Holmgren (2016)). Holmgren (2015) states that "extreme weather events, such as heat waves, drought, cloudbursts, storms, high flows and floods can, just like the sea level rise, quantitatively and qualitatively alter the water in the raw water sources upon which the drinking water supply is based".

In terms of water quantity, overall water availability is generally expected to increase in Sweden because of increased precipitation. However, a future increase in drought frequency and intensity during summer in southern Sweden may lead to water deficit (Holmgren, 2015). The main impact is expected in eastern Götaland, which is the part of Sweden with the lowest discharge (water flow in rivers) in today's climate. Increased evaporation will increase the number of days with low flows which may lead to water deficit locally (Holmgren, 2015).

In terms of water quality, a major risk in this context is associated with cloudbursts and flooding that trigger an enhanced transport of chemical and microbial pollutants as well as organic matter, e.g. in connection with erosion and landslides (Holmgren, 2016). Impacts of future changes in rainfall intensities on nutrient transport were investigated by e.g. Wu and Malmström (2015) and Messing et al. (2015), with the latter quantifying how much the transport of phosphorus from clay soil increases with increasing rainfall intensity (for single events). Several studies have investigated how different water quality aspects, notably acidification and dissolved organic carbon (DOC) concentrations, are affected by extreme or unusual events or episodes such as cloudbursts, droughts and snowmelt in Swedish conditions (e.g. Erlandsson et al. (2010); Moldan et al. (2012); Tiwari et al. (2018)). The studies demonstrated a distinct impact of climate extremes on water quality and e.g. a potentially increased acidification in lakes (Erlandsson et al., 2010).

Other potential impacts of extremes on drinking water quality are related to increased frequencies of algal blooms and undesirable microorganisms during heat waves (Holmgren, 2016).

Concerning sewerage, one expected consequence of more intense rainfalls is an increased risk of sewer overflows, i.e. untreated storm water being transported not to a treatment plant but directly to recipient. This may substantially disturb drinking water production. Further, flooding may indirectly affect sewer systems and their operation, e.g. increase the risk of power failure potentially causing pressure drops during which the risk of polluted water entering the systems increases (Holmgren, 2015). An analysis of the impact of climate change on the main sewer system in Stockholm was made by Olsson et al. (2011). A substantial increase in sewer overflow events was found as well as an enhanced flood risk. Similar analyses have been performed for (parts of) the cities Kalmar (Olsson et al., 2009) and Arvika (Olsson et al., 2013). The impact of future changes in rain-on-snow events on urban runoff was studied by Moghadas et al. (2017), who concluded that more frequent runoff and flooding problems are to be expected.

4.2 TECHNICAL DISTRIBUTION SYSTEMS

During the late 1990s and early 2000 years, about 40% of power failures are related to weather, and climate change is expected to increase the pressure (Veibäck and others, 2009). Overhead cables may face an increased risk of damage, especially in a situation with extreme wind speeds together with wetter soil and less ground frost (Holgersson et al., 2007). Power companies have started to address that risk by partly drawing cables underground. For overhead cables, the stability of the pillars is reduced and there is an increased risk of trees falling on the cables. This is not an issue for underground cables, but on the other hand these may be sensitive to intense rainfall, flooding and extreme sea levels. All cable types are not watertight and may be damaged by corrosion.

The Swedish power grid is divided into three components - national grid ("stamnätet"), regional grid and local grids - with different levels of robustness. Landslides could potentially affect the national grid, especially if it coincides with other types of disturbances, with consequences for the entire country. The regional and particularly the local grids are more vulnerable to landslides, although today it is not considered a major threat (SMHI, 2014).

An investigation of how high temperatures and heat waves affect technical systems was performed by MSB (2014). In terms of power supply, the most severe threat is related to malfunctioning of heat-sensitive technical components that may lead to distribution failure. Another identified risk is that the operation of nuclear power plants need to stop when cooling water becomes too warm (vanVliet et al., 2013; Jylhä et al., 2018). An analysis of power reliability in Sweden focusing on extreme events, using the storm Gudrun in 2005 as an example, was performed by Gündüz et al. (2017), who recommended that more resources are needed to secure power reliability in a future and more extreme climate.

4.3 TRANSPORT AND COMMUNICATION

According to Holgersson et al. (2007) technical infrastructure, especially roads and railways, will be affected by an increased risk of flooding in lakes and water courses. Also associated erosion and landslides may put roads and railway transport at higher risk, as may higher wind speeds. Bridges that constitute a particularly vulnerable part of the road and railway infrastructure are susceptible to a large number of risks related to extreme climate and weather events (Nasr et al., 2019). More intense rainfalls may increase the number of accidents caused by aquaplaning. Another aspect is that railway tracks may be negatively affected by extended heat waves. A common problem experienced during recent summers is buckling (solkurva), but also various technical components are sensitive to heat (relays, switches, etc.). During heat waves, train transport cannot be carried out according to schedule because of exceeded heat tolerance in technical components and cooling systems (MSB, 2014).

Power failure by e.g. flooding will affect telecommunication, either as reduced capacity or as a total stop. Many large fibre cables are placed in bridges that may collapse in case of extreme high flows. Such an accident may affect both local and remote telecommunication nodes. Kalantari et al. (2014) investigated how future changes in extreme rainfall will affect the design of road structural components (pipe bridges and culverts).

In Holgersson et al. (2007) it was concluded that shipping is unlikely to be much affected by climate change, although some negative impacts of extreme weather was mentioned. Extreme sea levels may make landing difficult in some harbours and require adaptation. Landslides caused by high flows in narrow channels are another potential risk, as is the potential increase in extreme wind speeds. Nyberg et al. (2014) highlighted the multiple objectives associated with water regulation and flood risk reduction in Lake Vänern. Another risk for shipping is that of reduced visibility in connection to future fogs containing more water, which leads to reduced visibility (Nasr et al., 2019).

4.4 FORESTRY

Forests may be affected by mainly two types of extremes, winds and drought (e.g. Samuelsson et al., 2012; SMHI, 2014; Eriksson et al., 2015). Concerning the impact of windstorms, during the last half century there is a clear trend towards increasing wind damage Nilsson et al. (2004), Holmberg (2005), Nilsson (2008) despite the lack of a corresponding trend towards a more severe wind climate (see section 3). Thus, the main drivers for the increase of wind throw is instead increased forest area, more dense forests and changing forest management practices, as well as the trends toward less ground frost and wetter soils during the main storm season (Eriksson et al., 2015). As the two latter are climatic drivers brought about by climate change, the present trends are expected to continue into the future (e.g. Subramanian et al., 2018) under the conditions of a warming climate. Summarizing, the overall impact on risk for wind throw is not straightforward because the climate change is expected to lead to changes in the forest composition and tree species' relative competitiveness (e.g. Eriksson et al., 2015; Ikonen et al., 2017; Subramanian et al., 2018).

Drought may affect forestry in two ways, by changing the conditions for different species due to drought stress and by an increased risk of forest fire. Concerning the former aspect, Bolte et al. (2010) concluded that in southern Scandinavia the drought-sensitive Norway spruce will lose competitive ability compared with European beech. The dysfunction of Norway spruce during drought was further investigated by Rosner et al. (2018). It is a problem that might become even more pronounced in the future, in particular at sites with conditions (Jönsson and Lagergren, 2018).

Both drought stress and wind throw increases the risk for severe outbreaks of the spruce bark beetle (Ips typographus). The principal mechanism is that bark beetles thrive on spruces having decreased resistance due to drought stress or being recently wind thrown. This allows the population to rapidly grow to a size where attacks on healthy tree stands out-compete the natural resistance capacity of the trees. The risk for severe bark beetle outbreaks is further aggravated because droughts are often concomitant with heat spells. The reason is that the bark beetle phenology to a large extent depends on temperature sums and favourable (i.e. warm enough) swarming conditions. A current hands-on example of this interaction between climate extremes and bark beetle outbreaks is dry and warm summer of 2018 leading to severe bark beetle problems in 2019.

Forest fires are expected to increase with climate change. Estimations of future changes simulated by different fire risk models show a consistent increase in the length of the fire risk season by up to one month and severe periods for the south-east of Sweden in a high emission scenario for the end of the century (Sjökvist et al., 2015; Berg et al., 2017). However, for other parts of Sweden, the models disagree even on the sign of the changes. Differences are likely due to how top soil moisture is calculated in the different models, and which meteorological variables are included in the calculation, e.g. relative humidity and wind speed (Berg et al., 2017). The complexity of the calculation must be balanced with the uncertainty in the observed and modelled variables, and the best procedure is still an open question.

The results in Drobyshev et al. (2014), based on historical fire events, pointed towards the presence of two well-defined zones with characteristic fire activity, geographically divided at approximately 60°N. A north-south division of Sweden was also suggested by Yang et al. (2015), with a higher future risk in the south and a lower in the north (Berg et al., 2017).

The forestry sector's – and its various actors' – perception of risk and management of impacts of weather and climate extremes in present day climate as well as strategies for the future have attracted substantial interest in the Swedish adaptation discourse, both drawing on stakeholder interviews or modelling studies, or a combination thereof [e.g. Andersson et al. (2015), Jönsson et al. (2015), Keskitalo et al. (2015), Andersson and Keskitalo (2016), Keskitalo et al. (2016), Lidskog and Sjödin (2016), Andersson and Keskitalo (2018), Andersson et al. (2018), Heltorp et al. (2018).

4.5 AGRICULTURE

Agriculture is expected to be more impacted by extreme weather in several different ways. Related to water, increases in heavy rainfall and flood risk are expected to require a need for re-designed and improved drainage systems. This problem is exacerbated by the current tendency of connecting urban drainage to agricultural systems when cities expand into rural areas. Also nutrient transport from (fertilized) agricultural land may increase, e.g. associated with erosion following intense rainfall (Messing et al., 2015)

Heat waves are another concern for both crop production and animal keeping. Today, many animal-keeping facilities are not designed for extended heat waves. Increased mortality has been registered at just over 30°C which suggests a need for improved ventilation to adapt to future conditions. Also, animal keeping consumes substantial amounts of water, both for drinking and for cleaning etc. (Larsson et al., 2013; SMHI, 2014). The impact of agricultural drought on irrigation demand, energy requirements and crop yield is investigated by Campana et al. (2018).

Increased heat waves were shown to lead to problems in milk production, including reduced animal growth rate, milk yield and reproductive performance (e.g. Das et al., 2016).

Furthermore, agriculture is highly dependent upon a transport systems, e.g. for food provision (both to and from the farm, in different stages of processing) and various services. An increased frequency of extreme-weather disturbances in the transport system will have direct impacts on management needs in the agricultural sector (SMHI, 2014).

4.6 HEALTH

Health is affected by extremes mainly through heat waves, intense rainfall, floods and landslides (Holgersson et al., 2007; SMHI, 2014). Heat waves have a direct impact on mortality, especially for vulnerable categories of people. Thus a future increase in heat waves may cause serious problems that require countermeasures to be taken. Thorough analyses of the impact of heat waves on mortality in Stockholm, including attribution of climate change impact, have been performed by Åström et al. (2013), Åström et al. (2013b) and Åström et al. (2018). The health impacts of heat waves may be exacerbated in case of elevated air pollution levels, e.g. originating from forest fires (Shaposhnikov et al., 2014). Another driver is demographic changes. Since elderly and people with chronic diseases are more vulnerable to high temperatures (Åström et al., 2011), an increase in these groups make the impact of extreme events more severe (Sierra et al., 2009). Also, changes in the behaviour of the population may alter the relationship between high outdoor temperatures and risk of premature mortality.

An increased frequency of high flows, floods and landslides, caused by intensified rainfall, includes the risk of affecting health negatively in different ways, including direct physical damage. Also, more intense rainfall and flooding are likely to increase the frequency of moisture damage to buildings, and consequently the presence of mold. Also, water quality may deteriorate with potential health impacts (e.g. Holmgren, 2016). Heavy rainfall has been found to be a useful predictor for faecal pollution (Tornevi et al., 2014). The efficiency at water treatment plants may be reduced at higher inflows than the plant was designed for (e.g. Tornevi et al., 2013) and the overflow of untreated water to recipients may increase. Such overflow facilitates the spread of infectious diseases as does e.g. flooding of pastures and farmland.

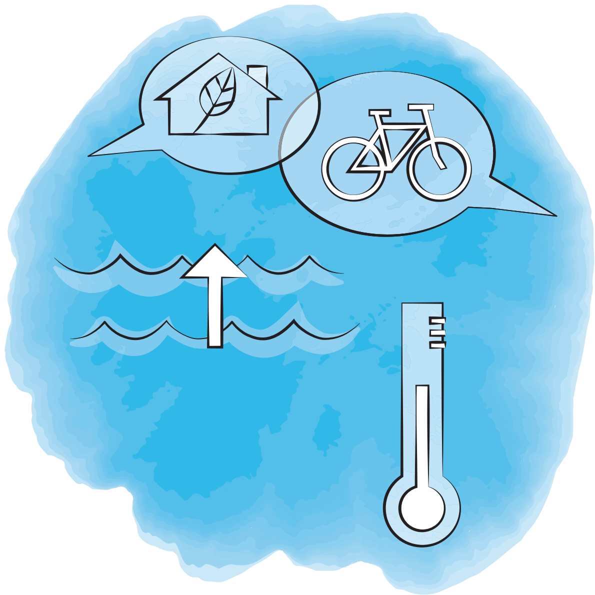
The impact of extreme weather events on elderly persons is discussed in Carter et al. (2016), where further a web-based tool for mapping and combining relevant indicators is presented.

4.7 BUILDINGS (AND CULTURAL HERITAGE)

The impacts of climate change on buildings and cultural heritage have been described in e.g. Holgersson et al. (2007), SMHI (2014) and Riksantikvarieämbetet (2013) and the main identified risks related to climate extremes may be summarized as follows:

- Flooding of waterfront buildings. Increased high/extreme flows and flooding along watercourses as well as extreme sea levels will put waterfront buildings at higher risk.
- Landslides and erosion. More intense rainfall, possibly in combination with changed groundwater levels, as well as increased sea levels are likely to increase the risk of landslides and erosion, putting exposed buildings at risk.
- Coastal erosion. Increased sea levels and stronger winds may substantially increase the problem of coastal erosion, potentially affecting buildings and infra structure.
- Sewer systems. The capacity of sewer systems risk being exceeded at higher-intensity rainfalls, potentially causing basement flooding and overflows.
- Building constructions. Intense rainfalls may increase the risk of moisture and mold as well as basement flooding; heat waves may increase the need for air cooling.

It may be remarked that both the extremes themselves as well as measures taken to reduce their impact may affect e.g. cultural heritage. Assessment of future hygrothermal (moisture and temperature) conditions and moisture loads related to buildings in Sweden have been made by e.g. (Nik et al., 2012; Nik et al., 2015).



»Reducing carbon emissions is no longer enough to halt the impacts of climate change. Many countries are realizing it's time to start adapting to a warming world.« (United Nations Environment Programme)

5. APPLICATIONS OF CLIMATE EXTREMES INFORMATION IN SELECTED USER STORIES

A continued and improved dialogue is needed between developers of climate models, producers of climate change scenarios, climate service creators and those who use the data for decision-making, for both public and private organisations. The current disconnection leads to barriers that prevent the efficient interaction between science and decision-making (Martins et al., 2019). Sources of disconnection include the lack of a common language across different disciplines and actors and the challenges in dealing with uncertainty. Questions such as how to turn a research result into useful information for a city planner at a local municipality, or how to explain the practicalities of the issues at stake to researchers in a way that they can transform it into research which can support or develop solutions, have no easy answer.

Communication of scientific information to non-specialized audiences is evolving from simply improving access to climate data into user-informed activities, with a move towards a demand-driven and science-informed approach where dialog is vital to determine what users really need and what science can offer. This section gives an overview of the progress of communicating climate information through a process of involvement with users which potentially leads to action. A short but significant list of examples of successful cases of communication for decision making is presented. These have often used a collaborative process, including joint work between societal actors and researchers, in order to produce information which is manageable, useful and understandable for decision-making and planning.

5.1 FROM COMMUNICATION TO CO-DEVELOPMENT OF SCIENTIFIC INFORMATION

Several sources give advice on rules for planning communication of scientific findings (see e.g. Key elements of the communication process in Moser and Dilling (2010); Fischhoff (2013); Cooke et al. (2017); Geiger et al. (2017)). The common core of these rules can be summarized in a guide around the simple questions of what, who, how, when and by whom, with an evaluation at the end:

- What: Clearly define what the purpose is of the commu nication, the main message and how to frame it, i.e. place the message in context relevant to the target audience.
- Who: Define the persons to whom the knowledge should be shared and map how much they already know and feel about the subject and their motives to listen to the message.
- How: Define the format of communication which fit with the target message and the target audience. Make a distinction on whether the audience should just listen to the message, or learn something, or act upon something that they have learned, and adjust the format accordingly.
- When: The timing is important, so try to find out if there is a more optimal time to engage around the scientific results.
- By whom: Credibility and trust should preferably guide the choice of sender/communicator of the message/s.
- Result of communication: Plan an evaluation of the activity, related to the aim, message and expected impact.

The communication guide above is, however, still a reminder of a one-way type of communication where the sender (in our case a researcher) decides to communicate a message (or result) to a receiver (students in a lecture, the local politicians and planners, or researchers within another discipline). This type of communication has increasingly been replaced by a framework where information for decision making (such as e.g. planning for climate extremes in a changing climate) is co-designed and co-developed through an interactive process (in a participatory model) involving the researchers, users and intermediary facilitators (see literature reviews on climate communication by Pearce et al. (2015), and Moser (2016)).

In another review dealing with seasonal climate forecasts, Dilling and Lemos (2011) emphasize that working in an iterative way, coming back to discuss around the table with professionals, is crucial for putting research knowledge into use by professionals in policymaking.

The concept of dialogue has been increasingly used in climate science communication, with scientific arguments to do so often coming from other research disciplines, such as the social sciences, and the business world. In Sweden, the concept of dialogue and iterative interaction has been a part of the process of communicating climate change information for some time. With the governmental task handed out in 2005 to assess the vulnerability and consequences of climate change in Sweden a large stakeholder process developed to include expertise from different sectors and professions. For the municipality officers the document produced by the special Commission (Climate and Vulnerability, 2007) acted as a reference point, as its development and launch was the start of a more constructive dialogue in Sweden, about how to address the vulnerability to future climate change. Involvement of stakeholders has since then further developed within the field of climate services such as those provided by the Swedish Meteorological and Hydrological Institute (SMHI) (Kjellström et al., 2016), with such a collaboration identified as a an important pathway for work in adaptation both on the local and national level (Andersson et al., 2015; Climate and Vulnerability, 2007).

There are several descriptions from different sectors in Sweden, on how to best involve stakeholders, how to set up a good dialogue and how to communicate and develop research jointly between societal actors and researchers for use in policy and decision-making. Some of these descriptions focus on forestry, like e.g. Jönsson et al. (2014) who looked at the chain of knowledge transfer from researchers to officials, advisors and private forest owners. One of their findings was that forest officials prefer synthesised research reviews, in an understandable language, rather than scientific articles or longer comprehensive state-of-the-art reviews. Further, André and Jonsson (2013) have been looking at how local experts in dialogue with scientific experts make sense of scientific knowledge and use it. They found in their focus groups of local forest experts and forest owners, that they often used past weather events, experienced by themselves, parents or grandparents, to relate to the new information, and ideas of how to adapt, which André and Jonsson (2013) refer to as an anchoring device. The storm Gudrun in 2005 acted as a starting point and reference point for several of the forest experts.

Climate change is a difficult subject to communicate (see for example Tyndall Centre's working paper "The challenge of communicating unwelcome climate messages", Rayner and Minns (2015)). Moser (2014) argues that nowadays it's easier to communicate adaptation since climate change is finally "real, local and tangible" and that communicating adaptation might be easier than communicating about climate science and mitigation policies because it offers some immediate co-benefits (disaster risk management, urban renewal, conservation, innovation or economic development).

Changes in extreme weather and climate events are the primary way that most people experience climate change. The science of attributing extreme weather and climate events has progressed in recent years to enable an analysis of the role of human activity while an event is still in the memory of the public (Lewis and Karoly, 2013; al., 2016; Stott et al., 2004). However, the communication of this science outside the extreme event scientific community has not fully reflected these advancements (Hassol et al., 2016). This is an issue of communication as well as of science (Hassol et al., 2016). Extreme weather events offer the possibility of communicating about climate change in a way that connects directly to people's lives and therefore can be used to start a discussion about adaptation (Demski et al., 2017). Although recent research suggests that the personal experience of extreme weather has only a short-lived effect on what people think about climate change (Konisky et al, 2015), articulation of scientific linkages between climate and events, and accurate reporting can lead to more serious planning to adapt to changes, and more relevant action on climate change (Hassol et al., 2016).

SPECIFICS ON PRESENTING DATA

The appropriate development of graphical visualisations is a central component in communicating climate science research findings. With a growing demand for climate information to guide climate change adaptation decisions (Hewitt et al., 2012) there is increasing interest and pressure to ensure that data presented is aesthetically attractive and tailored for specific user communities (Daron et al., 2015).

The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. It provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation. It is therefore the world's most important source of climate information for decision making.

Within the IPCC-process the presentation of data and information in a comprehensible way has been very important. However, research suggests that IPCC figures are not easily understood (see the analysis by McMahon et al. (2016) and Fischer et al. (2018)). In response to calls to enhance the communication of future IPCC outputs Harold et al. (2017) produced recommendations to help IPCC authors enhance the accessibility of data visuals in future reports and assessments using the MADE principle: consider your Message, your Audience, the Design of the visual, and its Evaluation. The recommendations were as follows:

1. Identify your main message
2. Assess your audience's prior knowledge
3. Consider how your audience 'thinks'
4. Choose visual formats familiar to your audience
5. Reduce complexity where possible
6. Build-up information to provide visual structure
7. Integrate and structure text
8. Avoid jargon and explain acronyms
9. Use cognitive perceptual design principles
10. Consider cognitive aspects when using digital animation and interaction
11. Consider cognitive aspects when visually communicating uncertainty
12. Test visuals to check comprehension

IPCC figures traditionally present future climate impacts over time. Sharpe (2019) argues that a more appropriate way of communicating the risks of climate change would be to produce assessments of the likelihood of crossing a certain threshold as a function of time. Such thresholds would be more relevant for policy makers since they would represent events or situations society wishes to avoid (ex. a 2°C warming limit, the height of sea level that leaves a certain island underwater or the temperature that exceeds a certain crop tolerance). This would provide a clearer picture of the risks of climate change and help inform the decision-making process (Sharpe, 2019).

Building on the work by Harold et al (2017), the IPCC has assembled a team to co-design the key visualizations of IPCC's Summary for Policymakers of the Special re-port on 1.5°C (Masson-Delmotte, 2018). The work carried out for the IPCC was presented at the webinar "Co-desig-ning the IPCC Special Report" (https://medium.com/infodesignlabposts/co-designing-scientific-information-the-key-visualizations-of-the-ipcc-special-report-on-global-1bbf041c72ef). Angela Morelli, information designer, reflected on how the work of designing information has changed dramatically in the last few years, from an order and delivery activity to a highly collaborative process where climate scientists, information designers, cognitive experts, communication specialists and users work together from the very beginning, exploring and stress-testing solutions and achieving a sense of joined ownership of the end product.

The co-design process is depicted in Figure 5.1. The target audience is the starting point; learning how the user decodes information and understanding the context in which information is to be used and processed are, according to Morelli, key-insights that guide the design. On the other hand, designers need to work very closely with the authors of the data, mastering the content and building a deep understanding of the nature of the data and the science that underpins it. The next step is organizing the data, this is what allows turning the data into information; this is a time consuming process where different ways of organizing the data are explored by building different visual narratives. The information is then presented to the audience, and if done effectively will lead to knowledge. Wisdom is the ultimate level of understanding, is the result of reflection and introspection. Knowledge and wisdom can then lead to action and change. This is however not as simple as the diagram shows, for different reasons: 1) different users, scientists, designers and stakeholders are involved in the process; 2) cognition is a complex process (the information is mediated through the brain which interprets the information); 3) as humans beings users assess how the information received is going to affect their lives, context and values; if the information received threatens those the user will refuse to accept it even though there is scientific evidence behind it; 4) even if the information is communicated properly and understood, and leads to action that might end up not happening because of existing external barriers.

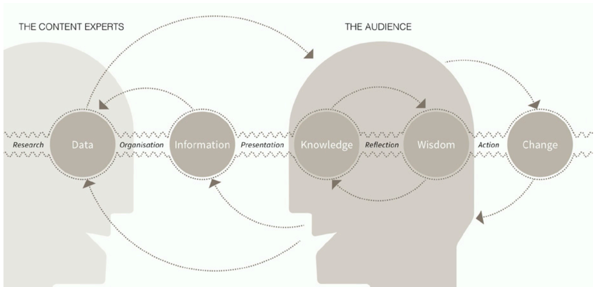


Figure 5.1 Co-designing process as present by Angela Morelli at the "Co-designing the IPCC special report" webinar, 30th January 2019, Oslo (https://medium.com/infodesignlabposts/co-designing-scientific-information-the-key-visualizations-of-the-ipcc-special-report-on-global-1bbf041c72ef).

5.2 SUCCESSFUL STORIES OF APPLICATION OF EXTREME CLIMATE INFORMATION

In the European context, the work within the European Adaptation Strategy launched in 2013 (COM2013:216 final), the development of the web portal climate-adapt.eu (hosted by the European Environment Agency) and the launch of the roadmap for climate services (Street et al., 2015; Street, 2016) have together accentuated and supported the idea of developing knowledge which can be of use to plan society.

Climate Adapt is a web portal developed to be a "one-stop shop" for information on climate, showcasing various examples of implemented solutions of adaptation to climate change. This type of online databases of good examples can be seen as a tool to enhance knowledge and spread good new ideas. There are additional websites, books and articles which illustrate how climate information has been used in specific situations which may be of interest to professionals in a decision making process. In Sweden the Knowledge Centre for Adaptation to Climate Change, established in 2011 at the Swedish Meteorological and Hydrological Institute (SMHI), has gathered good examples in order to share knowledge on how to adjust, adapt and plan in the context of future climate change. These examples, or cases, are on display at Climate Adaptation Portal. Table A.1 (in the Appendix) lists a collection of websites displaying cases or good examples related to adaptation to climate change.

For a better understanding of what can be done, considering insights of usability, graphical understanding and the organizational structure of information flow, as described above, we chose to zoom in on examples which have been performed or implemented already, and made use of climate extreme information. These examples, summarized in Table 5.1 and further described below, were chosen according to the criteria established in section 2 and are expected to give inspiration for other practical applications. The last entry of the table - Green infrastructures in cities – concerns a collection of cases not covered in this report but widely covered in the report by Persson et al. (2018) from the Formas funded project GI-Nord (Green infrastructure and climate in Nordic cities, today and in the future: state-of-the-art and knowledge gaps on interactions and impacts). All the stories described take place in Sweden, with the exception of Story 5 considering a new school building adapted to climate change in the UK (a similar case was not identified in Sweden, not necessarily meaning that it doesn't exist). Story 4 concerning the protection against high sea levels brings together a German case (already implemented) with a Swedish project in Vellinge still not implemented; the objective here is to show how former experiences can and should be used to inform new decisions.

TABLE 5.1 SUCCESSFUL STORIES OF APPLICATION OF EXTREME CLIMATE INFORMATION

Case study name	Climate extreme(s) addressed	References and contact for further information
1. Improving healthcare preparedness for heat waves in Skåne (Sweden)	Heat waves	In Swedish: https://www.smhi.se/klimat/klimatanpassa-samhallet/exempel-pa-klimatanpassning/battre-vardberedskap-for-varmeboljor-i-skane-fordjupning-1.122873?l=null; https://skl.se/download/18.1e80a68614cd1869610de9e5/1429793350645/Beredskapsplan-och-varningssystem-for-varmeboljor-skane.pdf In English: http://www.klimatanpassning.se/en/cases/better-healthcare-preparedness-for-heat-waves-in-skane-1.137456 Peter Groth, Public Health strategist, Region Skåne name.surname@skane.se
2. Reducing flood risk in transport infrastructures along the Göta river valey (Sweden)	Sea level rise Floods	In Swedish: https://www.smhi.se/klimat/klimatanpassa-samhallet/exempel-pa-klimatanpassning/minskad-oversvamningsrisk-for-vag-och-jarnvag-fordjupning-1.102271; https://www.smhi.se/polopoly_fs/1.130362!/klimatologi_49.pdf; https://www.sweco.se/vart-erbjudande/projekt/goteborg-skydd-mot-oversvamningar/ In English: http://www.klimatanpassning.se/en/cases/reduced-flood-risk-for-road-and-railway-1.141916 Jan Ekström, Geotechnical strategist , Trafikverket name.surname@trafikverket.se
3. Protection against high sea levels in Timmendorfer Strand (Germany) and in Vellinge (Sweden)	Sea level rise Storms Floods	In Swedish: https://vellinge.se/planer-och-projekt-i-Vellinge-kommun/aktuella-byggprojekt/trafik-och-infrastruktur/skydd-mot-hoga-havsnivaer/ https://www.sweco.se/vart-erbjudande/projekt/falsterbonaset/ In English: https://climate-adapt.eea.europa.eu/metadata/case-studies/timmendorfer-strand-coastal-protection-strategy-germany; https://climate-adapt.eea.europa.eu/about/climate-adapt-10-case-studies-online.pdf Vellinge Kommun vellinge.kommun@vellinge.se Jacobus Hofstede, Ministry of Energy, Agriculture, Environment and Rural Areas name.surname@mlur.landsh.de
4. Irrigation ponds for agriculture in Gotland (Sweden)	Droughts	In Swedish: https://www.smhi.se/klimat/klimatanpassa-samhallet/exempel-pa-klimatanpassning/bevattningsdamm-for-jordbruk-1.118563 In English: http://www.klimatanpassning.se/en/cases/irrigation-ponds-for-agriculture-1.141772 Andreas Nypelius, Lokrume Nyplings, Visby nypelius@live.se
5. Designing a climate resilient school in Worcestershire County (UK)	Heat waves Storms Floods	In English: https://www.ukcip.org.uk/designing-a-climate-resilient-school/ In Swedish https://webbutik.skl.se/sv/artiklar/klimatanpassning-och-nybyggnation.html
6. Green infrastructures in cities (Sweden)	Heat waves Floods	In Swedish: http://smhi.diva-portal.org/smash/get/diva2:1272429/FULLTEXT01.pdf In english: https://www.smhi.se/en/research/research-departments/air-quality/scientific-focus/g-i-nord-green-infrastructure-and-climate-in-nordic-cities-today-and-in-the-future-state-of-the-art-and-knowledge-gaps-on-interactions-and-impacts-1.139226 Jorge Amorim, SMHI name.surname@smhi.se

CASE 1. IMPROVING HEALTHCARE PREPAREDNESS FOR HEAT WAVES IN SKÅNE

Context

The heatwave in southern Europe in 2003 led to a series of initiatives at national and international level. In 2008, the World Health Organization (WHO) issued a guide with the purpose of improving public health responses to heat waves. In Sweden, in 2011 the Government's assignment for the study of the "Effects of heat waves and the need for emergency response measures in Sweden" emphasized the absence of local contingency plans for heat waves and the need in municipalities for education and information, written guidelines and instructions for both the general public and staff in health care services. To cover these needs, Skåne's region draw up an action plan with a special focus on the elderly as a risk group.

The contingency plan

In June 2014, Klimatsamverkan Skåne (a climate partnership between Region Skåne, County Board Skåne and the region's municipalities) released its final report for a "Contingency plan and warning system for heat waves in Skåne", directed to elderly healthcare Skåne. Other counties have used it as a foundation for their own strategies and the Swedish Association of Local Authorities and Regions (Sveriges Kommuner och Landsting, SKL) sends it out to all Swedish municipalities every summer.

The contingency plan mainly consists of checklists aimed at the individuals who are especially affected by a heat wave and those in the welfare system with responsibilities in the area. Nurses and doctors, home care managers, and healthcare professionals each have their own specific checklist. In addition, information about who the vulnerable groups are, which symptoms can be caused by high temperatures, and what the symptoms in the long run can lead to is also included in the information sheets. General guidelines were made available for the elderly and their relatives for response in the event of severely high temperatures, information regarding symptoms of heat exhaustion and dehydration, and information about which medications can be adversely affected by heat waves.

The plan also includes a list of what is considered important to think about in the practical work, including the need to anchor the contingency plan in the organization, prepare the alarm chain, and prepare for the dissemination of information. The contingency plan is activated every time SMHI sends out a Class 1 or Class 2 warning.

SMHI's heat warning system

SMHI has since 2011 run a project to develop a warning system for high temperatures in Sweden. Umeå University first investigated the risk of high temperatures and it's relation to daily mortality increases and later a reference group including the National Board of Health and Welfare (Socialstyrelsen), the Swedish Civil Contingencies Agency (MSB) and representatives from municipalities and county councils, worked together with SMHI to design the final warning criteria:

- High temperature message: forecast showing that the maximum temperature will be at least 26°C for three consecutive days.
- Class 1 warning for very high temperatures: forecast showing that the maximum temperature will be at least 30°C for three consecutive days.
- Class 2 warning for extremely high temperatures: forecast showing that the maximum temperature will be at least 30°C for five consecutive days and/or that the maximum temperature will be at least 33°C three days in a row.

Pilot project

The contingency plan was first implemented through a pilot project that was carried out during the summer of 2013. The municipality of Rosengård in Malmö which is a densely populated inner city area in a metropolitan municipality, and Staffanstorp, a smaller municipality with low and sparse buildings, were considered suitable as test pilots for the project.

Checklists were distributed to all participating units prior to the summer 2013 test, and also made easily accessible electronically in the case of heat waves (or high temperatures) alarms. The evaluation of the pilot project showed that the participating organizations and particularly assistant nurses at home care and retirement houses, perceived that they had benefited from the checklists and that they contained the right information. On the other hand, the material was perceived as too long and a little difficult to navigate , and therefore the packaging of information and checklists have been afterwards adjusted so that each user finds their part easily

Occupational and environmental medicine contributed with medical expertise both before and during the pilot project, providing the plan increased credibility. Furthermore, having the social care and nursing staff involved throughout the entire project proved that the contingency plan had a practical anchorage.

Costs

The costs to develop the contingency plan amounted to about SEK 500 000, which have been financed by Region Skåne. The two more relevant costs were the internal recruitment in the form of a medical appointment set aside from the doctors' regular working hours and a project nurse employed for a limited period of time.

Future challenges

The plan will continue to be developed in the future. A great challenge already today is how to include people who can be at risk during a heat wave but who are not currently included in the care system. These include, for example, elderly people with incipient dementia, chronically ill, and young children. These may go to a health centre from time to time, but have no regular contact with the doctor/nurse.

CASE 2. REDUCING FLOOD RISK IN TRANSPORT INFRASTRUCTURES ALONG THE GÖTA RIVER VALLEY

Context

The Göta River is a 93 km long navigable river that drains Lake Vänern into the sea (Kattegat) at the city of Gothenburg, on the western coast of Sweden; nowadays it is the largest drainage basin in Scandinavia (Figure 5.2). Kattegat's sea level around Gothenburg is the most relevant factor for the flood risk along the river as it limits the drainage of Göta River. High flows in the river have less impact.

The existing road along the river was partially flooded at regular intervals, with the road being completely or partially shut down. A stretch of 22 kilometers, between Angeredsbron and Älvängen, was extra flood-sensitive (Figure 5.2). Coincidently at the same time that the project studies began, the UN Climate Panel IPCC issued its second report, with estimates of a sea level rise between 15 and 95 centimeters to 2100, with half a meter as the most likely.

Figure 5.2 Göta river map (left) (source: Wikipedia); stretch between Angeredsbron and Älvängen, with road and rail line running along a narrow strip of land between steep hills and the Göta River. (Photo: Björn Söderström).

ELEVATION OF ROAD AND RAIL

It was decided that the new road (Bana väg) and the railway would also go into the valley, despite exiting flood risks, and stability and subsidence issues demanding large geotechnical work. The planning of Bana väg, one of Sweden's largest infrastructure projects at the time, was initiated in the 1990s. It included the construction of double tracks for high-speed trains, a four-lane highway and a local road between Gothenburg and Trollhättan. Both road and rail were completed in 2012 under the responsibility of Trafikverket.

To avoid floods caused by future level rise, the new infrastructure needed to be elevated which would mean increased costs for the project. A cost analysis was conducted considering: the level of increase and the damage that a flood would cause for road and rail; and a balance between recurring maintenance costs or higher investment costs. The risk of flooding and the costs of damage caused by flooding were valued for the three levels which were then weighed against increased investment costs for each level. The final decision was that the railroad level would be slightly higher in view of major consequences of flooding, such as the impact on electrical systems. The final increase was up to 1.5 meters above current levels where flooding risk was greatest.

BanaVäg has been used as an example of road and rail climate adaptation within Swedish authorities.

Costs

The cost of the entire project BanaVäg i Väst was SEK 13.6 billion, which was financed by the Swedish Road Administration and Banverket. A relatively large part of the sum, over one billion kronor, was spent on geotechnical measures to limit subsidence and reduce the flood risk. When comparing costs for different height levels, an increase of half a meter was estimated at 50-60 million.

Future challenges

The sea level scenarios on which the calculations were based have changed since then. With the uncertainty, both in terms of subsidence and sea level, some flexibility was required in the infrastructure. By taking into account sea level increase in execution on the bridges that cross the infrastructure, space for future increases in road and rail was also created. In the future, a renewed analysis of future water levels in Göta river may mean that the road and rail elevation level needs to be re-evaluated.

During 2017, the Swedish Civil Contingencies Agency, (MSB - Myndigheten för samhällsskydd och beredskap) carried out a review of the areas with significant flood risk in, and the Göta River one of the areas identified. Vänern and the Göta River are a unique area with a complex problem picture. Many of today's problems risk getting worse in the future as a result of the ongoing climate change (Figure 5.3).

Intresse	Dagens klimat	Framtida förändring
Bebyggelse Jordbruk Infrastruktur	Stor översvämningsrisk i Vänern och skredrisk i Göta älv	Ökad översvämningsrisk och skredrisk
Dricksvatten i Göteborg	Beroende av ett relativt högt vattenflöde i Göta älv. Problem vid höga havsnivåer. Stora konsekvenser vid ett skred.	Ökad risk för låga vattenflöden i Göta älv. Höjning av havsnivån. Ökad skredrisk.
Sjöfart	Problem vid låga nivåer i Vänern och vid höga flöden i Göta älv.	Ökad risk för låga nivåer. Vanligare med höga flöden i Göta älv.
Vattenkraft	Stor elproduktion.	Osäkert hur vattenkraften i Göta älv påverkas.

Figure 5.3 The most important issues around Vänern and the Göta River for today's climate and future changes.

One important issue is how large the release of water in the Göta River is possible with regard to flood risk, sea level elevation and technical limitations at the power plants. Rising sea levels in combination with heavy rainfall are expected to further increase flood risk in Gothenburg, therefore two external protection gates are planned. Sweco has carried out a preliminary study on how external protection gates can be designed to protect Gothenburg from flooding (Figure 5.4). Costs for design, construction and long-term maintenance are estimated to be between SEK 10 and 20 billion.

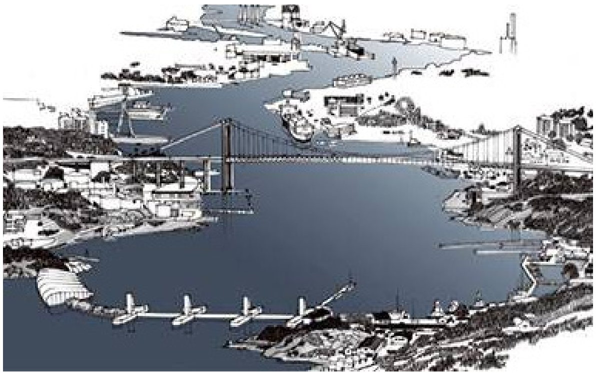


Figure 5.4 SWECO's illustration of protection gate near Älvsborgsbron.

CASE 3. PROTECTION AGAINST HIGH SEA LEVELS IN TIMMENDORFER STRAND (GERMANY) AND IN VELLINGE (SWEDEN)

Here two cases are covered, both concerning adaptation to sea level rise: the first one for Timmendorfer Strand in Germany where a solution is already in place, and the second for Vellinge municipality in Sweden where the solution is still not implemented. These two stories were brought together with the goal to highlight how former experiences can and should be used to inform new decisions.

I) TIMMENDORFER STRAND (GERMANY)

Context

Timmendorfer Strand is a coastal town on the Baltic Sea, in northern Germany, a large part of it laying no more than 3 meters above sea level. Main threats from climate change will come from impacts due to sea level rise and storm floods. An analysis of IPCC projections combined with regional modelling revealed that the main coastal flood defence (which was a natural beach ridge with a maximum height of about 3.5 m above mean sea level) was insufficient to ensure the safety of the population and the economic assets at Timmendorfer Strand.

Objectives and approach

In face of the described challenges (climate related threats and their intensification) and given that mean sea level rise in the region amounted to approximately 0.15 cm per year between 1900 and 2000, an adaptation project was started. The objectives of the project were:

- to increase risk awareness and communication
- to discuss appropriate solutions based on the community's values and needs with community members, and to renew the coastal flood defence structure.

It was clear from the beginning of the project that an appropriate coastal defence solution for the area could only be achieved with the active participation and acceptance of the local population, therefore a participatory approach was followed in the project.

The definition of the coastal defence concept followed three steps: assessment of socio-economic values, sensitivity analysis, and an ideas competition. Firstly, the socio-economic assessment revealed the potential damage in case of a flooding, which highlighted the need for improved coastal flood defence. Socio-economic parameters, like persons employed, tourist bed capacity, economic assets, or yearly gross value added were evaluated. This set the basis for the second step: a sensitivity analysis conducted through a participatory approach. Possible future developments under different sea level rise scenarios were simulated at different stakeholder events. The results of this step then formed the basis of the third step: an "ideas competition", where four engineering offices were asked to develop innovative ideas for coastal flood defence measures.

Discussions about an integrated coastal flood defence concept for the community of Timmendorfer Strand started in 1999; the project was concluded in 2011.

The solution - Seawalls and jetties

The agreed coastal flood defence measure was a sheet pile (sections of sheet materials with interlocking edges that are driven into the ground to provide earth retention and excavation support) wall integrated in the natural beach ridge ensuring the protection of the area up to a storm flood with a water level of 2.50 m above mean sea level.
A higher wall was not supported by the majority of the local stakeholders due to the expected consequences on tourism, the main economic sector in the community. Moreover, to improve local acceptance of the defence measures, glazed retention walls were built close to cafes, thus enabling the view of the sea (Figure 5.5).

Figure 5.5 Timmendorfer Strand beach and design of the coastal flood defence measure (the glazed retention walls increase the attractiveness of the area for visitors and local citizens)

Stakeholder Participation

The major outstanding aspect of the implementation of the coastal flood defence strategy in Timmendorfer Strand was the participatory approach through which nine working groups meetings and two public meetings were held. More than 50 local stakeholders (coastal protection authority, fishermen, tourism representatives, local residents and community authorities) were involved. The focus of these meetings was the analysis of how different coastal flood defence measures would affect the community.

As a result of this approach, the participants supported the results of the sensitivity analysis, recognized the long-term risk for the coastal area, accepted responsibility, and "evolved from sceptics to advocates of an integrated coastal defence concept". The participative process had a strong component of awareness rising and avowal of proposed coastal flood defence measures.

Costs and Benefits

Costs, including investment and maintenance costs as architecture finishing and landscaping project costs, were estimated for two climate scenarios (with sea level rise of 30 cm and 50 cm). The implemented measure was compared to a business-as-usual scenario, with no implementation of coastal defence. For both scenarios, the estimated benefits exceeded the costs of the measure: net present value ranged between 92 and 220 million euro, with estimated benefits 4 to 8 times higher than the estimated costs, depending on the future scenario. The biggest costs estimated were the investment costs (around 30 million euro) and the main type of benefits the avoided damage due to storm surges (71.5 million euro and 170 million for the different scenarios in the period 2011-2100).

II) VELLINGE (SWEDEN)

In November 1872, the Baltic Sea area was hit by a storm, Backafloden, when the sea rose by almost 2.3 meters above the normal sea level. That time, almost 300 deaths were registered in Denmark and Germany, but as far as is known, no deaths occurred on the Swedish side. However, a total of a few thousand buildings were destroyed on both sides of the Baltic Sea. In January 2017, a storm caused the sea level to rise by 1.53 meters at Skanör: the harbour, the nature reserve Flommen and a number of properties were flooded.

The need for protection is not only due to the increasing number of extreme weather conditions. There is also a continuous slow rise in sea level due to climate change. This rise is not offset by any corresponding land uplift, not in the country's southernmost part where the land uplift after the last ice age has largely stopped.

Today, 21000 people live on the Falsterbonäset (31000 in the summer) - and there are up to 8800 highly valued properties in the area. SMHI foresees that the average sea level can be raised by up to one meter over the next 100 years; this in conjunction with storms and subsequent storm surges could have a big impact in the area. If the water level rises by 2 meters, 60 percent of the properties would be surrounded by water; if it rises by 3 meters the number increases to 95 percent.

Vellinge municipality, to which Falsterbonäset belongs, has been working for many years now to provide extended protection against floods. The municipality decided that the protection barrier in Falsterbonäset should be able to withstand that the sea rises up to 3 meters above its normal level. The chosen dimension is a trade-off between, with a certain margin, coping with the levels that have been measured historically and not making excessive interventions in the sensitive environment. The south side of the Falsterbonäs has largely a natural protection in the dunes, which is up to 7 meters high and nowhere less than 3 meters. There are also old embankments, from the time when trains were operated in the area , which are already working as protection but which are to be built on and reinforced.

In 2018, the City Council submitted the project for approval to the Land and Environmental Court in Växjö. The approval from the court, which is expected in 2019, is required in order to carry out the construction of the protection infrastructure. Not before 2020 will the construction work begin; it is expected that it will take around 10 years for it to be ready. The municipality is currently working on signing agreements with the landowners concerned by the protection and examining the possibilities for various funding support for the project.

3D visualizations of the coastal protection have been developed by the consulting company Sweco on behalf of Vellinge municipality (Figure 5.6)

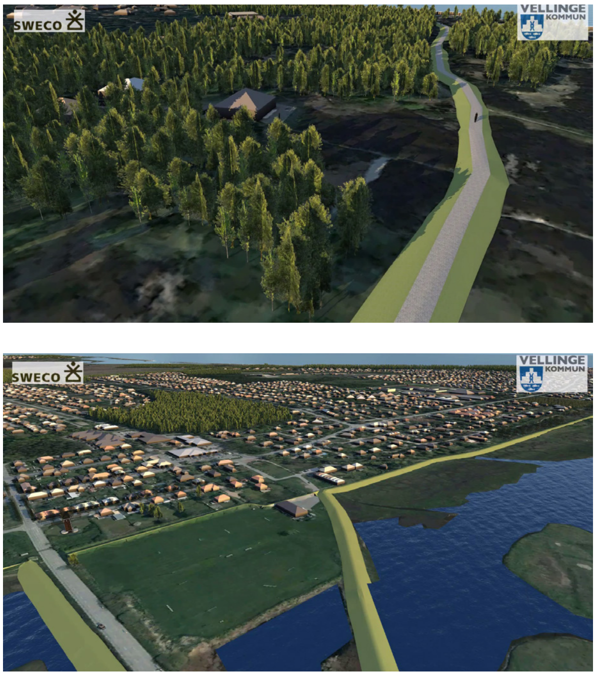


Figure 5.6 Protection barrier a) between Falsterbo and Ljunghusen, and b) at Skanör.(https://vellinge.se/planer-och-projekt-i-Vellinge-kommun/aktuella-byggprojekt/trafik-och-infrastruktur/skydd-mot-hoga-havsnivaer/).

CASE 4. IRRIGATION PONDS FOR AGRICULTURE IN GOTLAND

Context

Climate change will bring a longer vegetation period (growing season) in Sweden, which is a positive factor for agriculture. On the other hand, the risk of drought will also increase and with it the risk of reduction of the production. To optimally use the increased production potential, offered by a longer growing season, access to water and nutrients is required. A warmer climate also increases the risks related to new pests, weeds and viruses.

Studies conducted by SMHI for future conditions indicate a longer vegetation period (growing season), but also an increase in the number of days with low soil moisture in Sweden, and in Gotland specifically, despite increased precipitation (https://www.smhi.se/klimat/framtidens-klimat/lansanalyser#00_Sverige,t2m_meanAnnual,ANN). This is because the plants are active for longer periods, the temperature is higher and evaporation increases.

In Gotland, several farmers have already built or are planning to build ponds hopping to be able to improve water availability for their crops and animals.

Irrigation and drainage

The water needs of cultivated plants are normally not covered by the rainfall coming during the vegetation period. In the more water retaining soils there is a water reservoir that can be used by the plants. Lighter sandy soils have little opportunity to store water. In Gotland cultivated crops need about 90 millimetres of water per month compared to the normal monthly precipitation of 30-50 millimetres. Since Gotland' soil usually has a low water-storage capacity, water needs to be added. Water collected during winter time, be it surface water or from drainage pipes , can be used for irrigation during the growing season . In the Swedish climate, arable soil usually needs to be drained to avoid excessively wet conditions. So both access to irrigation and good drainage are important issues for agriculture.

Irrigation Ponds

In Gotland there are over 100 ponds. These are the main source of water for crop irrigation; in general groundwater and surface water from watercourses is not used. Creating ponds is a way to improve water availability for crops and animals, as well as to ensure a more even production for the farms. Water and nutrients are gathered in the ponds that are returned to the agricultural soil upon irrigation. This way, the water is slowed down and the nutrient load on the Baltic Sea decreases. Moreover, ponds often become attractive wetland areas for many breeding or resting bird species.

The implementation of irrigation ponds in two different Gotland farms, where vegetables and root vegetables are cultivated, is briefly described below.

I) IRRIGATION POND IN NYPLINGS FARM

Located 17 kilometres outside Visby in Lokrume, Nyplings farm cultivates vegetables, asparagus and root vegetables on 170 hectares of land. The decision to invest in an irrigation pond was motivated by the possibility to expand the vegetable cultivation and to have a more eco-oriented cultivation.

In order to construct the irrigation pond, the forest was first removed. The pond was built in 2013-2014 with varying depths, in accordance with the natural conditions; half the pond is about 7 meters deep and the other half is only 1 meter deep. Clay has been laid at the bottom and sealing has been made against the rock in some places. The storage volume is estimated at 70 000 m^3. The irrigated area is 90 hectares.

The pond costs were under SEK 1.3 million and the pump with 1.5 km of cables and machines approximately SEK 700 000. The County Administrative Board, through the Rural Development Program (Landsbygdsprogrammet) provided SEK 800 000 for the pond and SEK 150 000 for the other costs.

Farmers at Nypling's farm are very satisfied with the irrigation ponds. The measure has worked very well and the rainy autumn 2017 even made it possible to fill the pond with 100% self-filling. During the very hot summer of 2018 the pond was considered a great advantage in coping with such extreme conditions: the production yield was 25-35 percent higher than it would have been without irrigation from the ponds.

II) IRRIGATION POND IN NÄR

One of Gotland's largest irrigation ponds with a water mirror over 11 hectares is found in När. The pond is the result of collaboration between three family farms (meat and milk producers, potato growers and lawn growers); later another seven farms have joined and also the local golf club.

A 2.5 hectares pond was built already in 1979. The knowledge from that installation was the basis for the larger pond construction that began in 2005. In total, the new artificial lake comprises 16 hectares and accommodates 350 000 m^3 of rain and drainage water. At its deepest, the lake is 6.8 meters and the mean depth is 3 meters. During the growing season, when water is used for irrigation, the water level drops by about 10 cm per day. An irrigation facility has also been built together with three miles of buried pipelines.

The total cost of the artificial lake in När was SEK 6 million. Financial support was partially provided by the Rural Development Program.

Figure 5.7 Excavation and eastern part of the lake in När (top); irrigation pond at Nyplings as of September 2016 when the shallower parts of the pond were dry (bottom).

CASE 5. DESIGNING A CLIMATE-RESILIENT SCHOOL IN WORCESTERSHIRE COUNTY (UK)

Context

The Red Hill School project involved the replacement of a primary school built in 1965. The complete rebuild of the school was projected for a 60-year life span, and therefore, decisions made would have long-term consequences. Climate impacts had therefore to be taken into account in the project. The UKCIP Adaptation Wizard (https://www.ukcip.org.uk/wizard/) was used by the Worcestershire County Council to assess the impacts of climate change on a new school and to provide an initial outline adaptation strategy for the design and construction phases, and also throughout the design life of the building.

Risks and measures

The priority risks identified in the strategy were:

- Higher rainfall in winter, more intense periods, driving rain;
- Milder winters;
- Hotter drier summers;
- Increased wind speeds/extreme storms.

The £2.7 million Red Hill School project produced a low carbon building that is more likely to able to cope with climate extremes and to maintain a comfortable and robust teaching environment over its lifetime. Some of the adaptation features integrated into the school to help it to withstand climate change impacts include:

- a sustainable urban drainage scheme using swales, ponds and underground box storage;
- a rainwater harvesting scheme for part of the roof area, used for flushing toilets;
- other roof areas have a planted roof finish (sedum) to reduce run-off;
- wide gutters with emergency overflow points provide for periods of sudden intense rain;
- extra shade for students and teachers, provided by over hanging eaves and external canopies to the classrooms;
- zinc sheet roof coverings, with standing seams, that may be less vulnerable to high winds than roofing tiles;
- extract vents powered by small photovoltaic panels were installed to ensure all vulnerable areas were well ventilated, particularly wet areas like toilets and showers;
- heating system using heat pumps run on electricity from renewable sources.

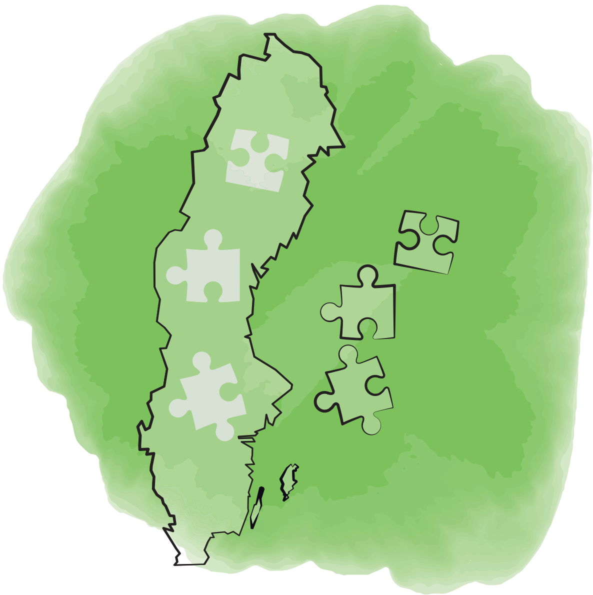
When deciding on aspects such as the location of buildings in the terrain, the building orientation, the thermal mass of building and the structural building materials, decisions were driven primarily by other site constraints and environmental consideration rather than climate impact concerns. However, the project team sought to mitigate some of the effects of these decisions by other means to assist resilience against climate change impacts.

Figure 5.8 Main entrance to the Red Hill School in Worcestershire; (http://house.speakingsame.com/school_img.php?id=2244&name=Red+Hill+Primary+School&region=Red+Hill)

In Sweden

In Sweden municipalities have a responsibility under the Planning and Building Act (Plan- och bygglag) to take climate risks into account when planning new buildings. Risks to be considered must include increased precipitation, rising sea levels and temperature changes. In order for the buildings to withstand the stresses of climate change, the municipalities may have to take special measures and, through conscious planning, ensure that new climate risks are not built in.

In their guide "Klimatanpassning och nybyggnation - tips och råd från kommuner som visar vägen" the association of Swedish municipalities and county councils (Sveriges Kommuner and Landsting – SKL) has collected some examples of municipalities that work strategically with climate adaptation issues which have recently started to review their work routines so that they think about climate change and extremes throughout the planning process.



6. GAPS IN KNOWLEDGE AND UNDERSTANDING

Substantial gaps exist in our knowledge about climate extremes to fully represent the climatology of extreme events, regarding quality and density of observations, regarding climate simulation system's abilities, regarding the potential for future changes of extremes, and with respect to exposure, vulnerability and related impacts on societal sectors. Extreme events are rare by definition and the less frequent the event, the more difficult it is to identify long-term changes. Global-scale trends of a specific extreme type are either more reliable (e.g. for temperature extremes) or less reliable (e.g. for droughts) than regional-scale trends, depending on the geographical uniformity of the trends in the specific extreme. In this report, we review existing findings. In this section about knowledge gaps, we present substantial remaining challenges, that include the usability of the observational information, the importance of different physical processes, implications of uncertainties and the capabilities of climate models. Results about the knowledge of different extreme types, from section 3, are combined here with knowledge gaps, in table 6.1. (at the end of this section).

6.1 GAPS OF PHYSICAL UNDERSTANDING AND IN MODEL-BASED FORECAST AND PROJECTION OF EXTREMES

Changes in large and small scale extremes of precipitation and other variables is affected by thermodynamic and dynamic contributions (Pfahl et al., 2017). The thermodynamic part is mainly controlled by temperature changes that imply a few percent increase of precipitation per degree Celsius. The more complex dynamic part is affected by changes in both large and small scale circulation and atmospheric stability, which can enlarge or mute the thermodynamic response.

Numerical models for climate and weather play an essential role for determining the importance of different processes and for quantifying the amplitude, frequency and composition of extreme events in the past and future. Therefore, process studies are often connected to model-based work. In climate simulations, calculations are carried out in spatial boxes with a certain width and thickness ("resolution"). The dynamic contribution to the occurrence of extremes is causing the most uncertainty in climate model projections of precipitation, both as a result of the representation of major teleconnection patterns such as e.g. the North Atlantic Oscillation (NAO), El Niño Southern Oscillation (ENSO) and the intertropical convergence zone (ITCZ). Also small scale dynamics of convective systems, as multiple cells or cells embedded in mesoscale convective systems, are poorly understood and not represented in typical climate models with coarse horizontal grid spacing of less than 3 km. Instead, the limited available empirical knowledge on the smaller scale processes is used. However, processes related to extremes can be better described in high spatial detail ("high resolution") in the models. This requirement can be fulfilled by so-called convection permitting climate models, which are emerging as the next generation of regional climate models. They operate at high spatial resolution, with grid spacing of 500 m - 3 km, and as a result are conceptually different from their lower-resolution counterparts in that they do not use physical parametrizations for deep convection.

The most relevant knowledge gaps with respect to process understanding and climate modelling abilities are described next.

A key need is to improve understanding of climate physical processes at convection permitting scales and their representation in the models. Moist convection is a very important source of extreme precipitation in nature, becoming the dominant mechanism for extremes at sub-daily scales and in tropical and monsoon regions, and its parameterizations have long been recognized as a large source of error and uncertainty in global and regional climate models. As a result, convection permitting models, not using convection parameterizations, offer enhanced capabilities to simulate present and future climate, including fully realistic timing of maximum precipitation within the diurnal cycle and considerably improved statistics of extreme precipitation intensities. In most existing studies, the model resolution is too coarse to give a realistic representation of extreme precipitation. With increasing temperature, that limitation of resolution prevents reproducing the full magnitude of increase in extreme local precipitation. Also, the timing and location of precipitation extremes depends on resolution; i.e. description of processes on the convection scale (e.g. Roy et al., 2007; Quintanar et al., 2012; Seneviratne et al., 2013; Winchester et al., 2017). Improvements in simulating extremes have been demonstrated for convection-permitting resolution of 500 m - 3 km (Leutwyler et al., 2017). Climate models on that km scale resolution need further development of the physical descriptions and computational efficiency. Furthermore, because of high spatial resolution, convection permitting (CP) RCMs are an invaluable tool for a wide range of studies and users. Examples include urban climate and the role of urban vegetated areas, and better description of climate change in mountainous areas and coastal zones.

The poor representation of cloudbursts in climate models affects our confidence in their projections on future climate. Several studies have sought to estimate how climate extremes change in a warmer climate by linking extremes to day-to-day variations in present day temperature or dew point temperature. It is, however, debated whether such studies physically link to future climates (Bao et al., 2017; Barbero et al., 2018). The link between environmental conditions, such as humidity and temperature, and cloudbursts is uncertain, especially in a climate change perspective. The uncertainties could be reduced by focused efforts on examining the link between precipitation extremes and variations in temperature and moisture, in observations and in climate models. The latter would require CP resolution without the need of convective parameterizations.

Hydrological catchment characteristics affect to a large degree the vulnerability for floods of different kinds. It is dependent on both the type of flood event, such as cloudburst, snowmelt, multi-day precipitation extremes etc., and on catchment characteristics, such as its size, slope, soil properties etc. Hydrological models can indicate extreme streamflow, but the impact is better modeled in hydraulic simulations that include computation of the flooded land area. Inventories of catchment characteristics are carried out for only selected catchments, and Sweden lacks a countrywide assessment of catchment exposure to different precipitation and flooding extremes. A gap is seen in a missing mapping of catchment areas which could be carried out by hydraulic models.

Soil-moisture conditions and vegetation affect extreme precipitation and temperatures, via evaporation and mechanical effects due to land/vegetation type (forest vs open land or urban). There is a coupling between soil moisture and precipitation so that increased evaporation or soil-moisture gradients lead to increased precipitation (Seneviratne et al., 2010; Guillot et al., 2015; Spracklen et al., 2018). On the European scale, larger surface roughness over forests decreases extra-tropical cyclone activity and consequently leads to decreased extreme precipitation. The mean precipitation is much less affected because of other compensating forest effects; for example, during summer the precipitation increases due to the soil-moisture feedback triggered by increased evapotranspiration (Strandberg and Kjellström, 2019). Uncertainties in the sign and magnitude of the response of climate extremes to changing land cover are large in model simulations (Davin et al., 2016), and as a result the different contributing mechanisms are under-explored. A knowledge gap is seen in the quantification of different mechanisms linking evaporation, evapotranspiration and precipitation and their representation in models.

The most harmful extreme events are rare combinations of different extremes, so-called compound events. Also the combination of extremes with simultaneous non-extreme conditions can lead to severe compound events. The interactions between the varying influences are barely understood and need to be examined as case studies for different geographical areas and compound parts. Thereby a multivariate perspective is necessary and past compound events need to be studied in combination with similar events in future climate scenarios to understand changes in mechanisms, occurrence frequencies, impact and possible mitigation measures. In addition, deep learning methods offer new opportunities to understand the interaction between variables (see below in "Gaps in observations").

Evapotranspiration, i.e. evaporation and plant transpiration, is becoming increasingly important in Swedish water balance calculations, as a result of rising air temperatures. The loss of soil and surface water can be large enough to offset increases in streamflow due to increasing precipitation, and thereby diminishing the flood hazard compared to today (Bergström et al., 2001). However, there are only few direct observations of this spatially heterogeneous variable, and further, a large uncertainty in estimation techniques for evapotranspiration in general. More research is needed on evaluation on evapotranspiration models best suited for Swedish conditions, and how large the impact on future projections might be.

Limiting warming to two degrees or less has become the agreed target for global climate policy (Paris climate accord). However, the consequences of that warming level for climate and weather extremes is not well known (Bärring and Strandberg, 2018). Very few global and regional scale studies exist, e.g. by Fischer and Knutti (2015), who conclude: "For 2 °C of warming the fraction of precipitation extremes attributable to human influence rises to about 40%. Likewise, today about 75% of the moderate daily hot extremes over land are attributable to warming." Northern Europe is often treated as part of a global or European-scale study and the above statement is based on the previous generation of climate models with rather coarse global model resolution, unable to describe km-scale processes, which are highly important for assessing extreme conditions. For Northern Europe no specific study on the extreme conditions under a specific warming level, making use of high resolution CP models is known. The consequences of warming targets in terms of extreme conditions need to be explored by very high resolution (3 km and finer) regional models, interpreting global climate change simulations for Sweden.

6.2 GAPS IN OBSERVATIONS

The detection of extreme events in datasets is typically carried out by algorithms that search for defined thresholds given by the outer margins of probability density distributions of given climate variables such as wind speed, temperature or precipitation. Clearly defined events can be found. The task becomes more challenging when considering composite events which combine a number of variables that only in combination create a high impact. Also, the amplitude of the impact, such as area of devastated forest or economical costs of a weather event, can be used to define an extreme event. That kind of composite or impact-oriented event definition can hardly be covered by traditional algorithms. Therefore, next steps in event detection need to take the impact into account. This could be done by developing deep learning algorithms, a form of artificial intelligence, that can be trained by high impact events related to observed transient composite events in the atmospheric and ocean. First indications for the potential of deep learning methods are given for example by Liu et al. (2016). Who provides a first approach to detecting extreme weather automatically without any prescribed thresholds, using deep learning.

Industrial structures with low probability but high consequence in case of failure, such as nuclear power plants (NPPs) may be subject to impact by atmospheric and/or oceanic extreme events. Potential risks arise from e.g. freezing rain, extended dry spells, heavy snow loads, large hail, strong winds, lightning and combined events such as high temperature combined with high humidity, heavy snowfall with high wind speed, and heavy rain with strong wind. Such extreme weather or marine events are known only with large uncertainty because they occur, by definition, only rarely (Jylha et al., 2018).

Scientific studies on recent and future extreme conditions can provide relevant information for designing, regulating and climate-adapting potentially vulnerable facilities. Results presented by Jylha et al. (2018) with respect to Finnish NPPs highlight the need to broaden the scope of research to support the design and adaptation of vulnerable facilities.

A practical gap is seen in a missing system for combining observations and knowledge about recent and future climate with specific high relevance for vulnerable industrial structures. In particular it would be helpful to:

- combine different observation variables to allow new conclusions on frequencies of critical events and combined events
- extend the observational data base towards inclusion of more historical observations
- investigate the need for additional or new monitoring variables and strategies
- to evaluate climate models with respect to their capabilities of simulating the extreme events and combined events with risk potential, and to formulate corresponding goals for model improvements
- to identify future frequencies and intensities of relevant extreme combinations and hybrid events.

Tornados in Northern Europe are still underreported in sparsely populated areas (see section 3) and it is difficult to detect trends in observational records that are not connected to changing population density and thus likely to changed reporting. A more representative reporting would be worthwhile because increasing temperatures and moisture contents in a warming climate provide favorable conditions for deep convection which in turn provides the base for potentially more frequent or intense tornadoes.

The apparent increase in tornado occurrence and damage (see sec 3) in combination with the problems of underreporting in sparsely populated regions is:

- motivating the need for better reporting and for exploring the use of newly employed instruments such as SMHIs recently upgraded doppler radar network.
- spurring research into remote sensing methods for improved detection of tornado damage in European forested regions (Shikhov 2018; Chernokulsky 2018).
- motivating usage of high resolution convective permitting atmosphere models (Gallo et al. 2016), for better assessing conditions for future tornado events
- Development of a tornado index for northern European conditions

6.3 GAPS IN KNOWLEDGE ABOUT IMPACTS

Impacts of climate extremes are multi-faceted and depend on exposure and vulnerability of a structure or system hit by the impact (see section 4).

Climate change mitigation research explores the consequences and impacts of alternative emission pathways during the 21st century and beyond, including the measures to curb greenhouse gas emissions and climate intervention such as carbon dioxide removal methods. Consequences express themselves by differences of mean climate, seasonal variations and extreme conditions. Most of mankind, represented by national governments, has committed to keep the global warming below an average of 1.5 or 2°C in the Paris climate accord. The consequences of different warming levels, such as the 1.5 or 2°C goal or higher levels, are largely unexplored on a regional and local level. The recent IPCC special report on the impacts of global warming of 1.5 °C (IPCC, 2018) identifies low confidence for quantifying changes of extremes in many regional areas. Also, little is known about alternative emission pathways exceeding the Paris goals, especially for overshoot pathways, which involve temporary peaks of atmospheric greenhouse gas concentrations.

Noting that mitigation research will become increasingly relevant in forthcoming years and decades, exploration of local effects of mitigation measures, especially in terms of climate extremes, for Sweden will be of paramount importance. That research will also be necessary to support national positions in international climate negotiations on future emission pathways and climate intervention.

The EURO-CORDEX project has generated large sets of simulations of recent and possible future climates, in about 10 km resolution. These datasets are well explored in terms of mean climate changes, but the information content regarding extremes is underexplored. Future studies could utilize the improved resolution with respect to much coarser global simulations, and update existing impact estimates.

Urban flooding

Flooding and inundation in cities are generally caused by short-duration (a few hours or less) rainfall extremes (cloudbursts). Thus the above discussed limitations with respect to describing convection and cloudbursts in climate models is a main obstacle also with respect to assessing climate impacts on urban flooding. Generally so-called climate factors are used to upscale today's design rainfalls to account for climate change impacts, but these are highly uncertain as they generally represent a (much) coarser scale than that of the actual physical processes. Conceivably the new generation of convection-permitting RCMs will allow for better estimation of the climate factors. Another key issue with respect to urban flooding concerns the fact that all cities are under constant development. Physical changes to the urban environment, such as densification and expansion (or the implementation of adaptive measures), can both exacerbate and counteract any climate changes with respect to flood risk. It is thus important to start focusing on integrated approaches, with interaction between natural and social systems (e.g. Kalantari et al., 2019).

Fire risk assessment

Extreme dry conditions, in combination with other factors, lead to increased fire risk. Risk maps can be calculated based on fire risk models, which have a clear potential for improvement. Current limits are:

- Forest fire risk models are to a large extent developed based on laboratory experiments on the drying out of different top-soil types, and there is no or at most few longer time series that can be used to evaluate their performance.
- Future assessments of fire risk is strongly affected by changes in relative humidity, which is a highly uncer tain variable in climate models and in observations. Whether the fire risk model accounts for relative humi dity or not can even change the sign of projected fire risk in northern Sweden (Berg et al., 2017).
- Fire risk during winter is not well covered. Fires in low vegetation in Norway during the winter 2013/2014 indi cates the importance of understanding both the large scale circulation impacts on preconditioning fire risk, and the operational aspects of having models suited for this type of fires in operational production also outside the main fire risk season (Berg et al., 2014).

Consequently, a way to overcome this gap of knowledge would be by enhanced observations of atmospheric and soil conditions, and improved scientific algorithms calculating the risk of fire.

Tourism

This field is rather underexplored, with vague and uncertain results (SMHI, 2014). There are only a few studies on the impact of reduced snow volume on tourism, but these focus on average conditions rather than on extremes. Tourism can also be expected to be affected by the rising sea level. However no extensive studies on the impact of extreme events on tourism have been found.

Fisheries

According to SMHI (2014), fisheries will mainly be impacted by average conditions, in particular the sea water temperature but also e.g. salt concentration. In terms of extremes, intensified winds and waves may affect the security of fishing boats as well as cultivation of e.g. fish and mussels, but more research is needed to quantify both the future changes and their impacts.

Natural environment and environmental targets

This topic is rather extensively covered in SMHI (2014), mainly in relation to changes in average climate conditions but with some examples also related to extremes such as flooding, drought and landslides. A more thorough and systematic synthesis on how climate extremes impact the natural environment and the possibility to reach environmental targets is recommended.

6.4 GAPS IN DATA PROCESSING

Bias correction methods

Climate change impacts can be simulated in so-called impact models, such as hydrological models describing water flow in rivers and ground. Many impact models, such as hydrological models, are sensitive to systematic errors (biases) in climate models, and methods generally called empirical bias adjustment (or bias correction) are employed to reduce these biases. However, there is no consensus on best practices in performing bias correc-tion, and the method chosen can sometimes give physical inconsistencies for trends of combinations of variables, both for present climate simulations and projected future changes. Bias adjustment must therefore be considered as a major uncertainty in impact assessments, which needs to be quantified and possibly reduced. Necessary future progress needs to address consistency between multiple variables, and scale-selective treatments, i.e. bias correc-tions targeted towards monthly, daily and hourly means with comparable accuracy.

Drought trends

Knowledge of drought changes relies on known past drought events. An analysis from historical observations for Sweden is yet to be completed and a clear identifica-tion of changes in trends at a regional level is not available. Studies on changes in drought trends have been conduc-ted so far on a European level, while studies for the Scan-dinavian region are limited to indirect methods such as tree-ring data reconstruction for accessing past regional soil moisture variability. In addition, areas such as Sweden require more elaborate water balance calculations to iden-tify changes in trends for droughts. Such calculations demand highly resolving and long timeseries of wind speed, humidity and temperature in addition to precipita-tion.

Attribution of extreme weather events to climate change.

A common question to recent extreme weather events relates to if they can be attributed to the ongoing anthropogenically driven change of the climate system. As the climate system has already changed, each and every weather event is to some degree impacted. Thus, a more relevant question would be - to what degree a certain event has become more plausible compared to that in preindustrial conditions. As climate observations are sparse or even non-existing for the preindustrial period, climate models are used for addressing differences between the present-day and preindustrial situation.

A proposed methodology for event-based attribution is summarized by Otto (2017) and includes the following steps:

i) stating what happened;
ii) defining the event;
iii) evaluating the climate models with respect to the event definition;
iv) estimating likelihoods;
v) interpreting and synthesizing results and
vi) communicating the results.

An advantage of climate models in this respect is that they can be applied repeatedly for simulations of the same time periods with the same forcing conditions to create large samples ("ensembles") of data which makes the conclusions more robust. Attribution of separate extreme events is a relatively new growing field of research. Examples of attribution studies can be found in the annual compilation of studies put forward by the Bulletin of the American Meteorological Society addressing extreme events of the preceding year. Knowledge gaps in these studies are related to inadequacies of climate models to represent relevant aspects of extreme events and to the size of ensembles, limiting the ability to draw robust conclusions due to limited statistical evidence.

6.5 GAPS IN COMMUNICATION FOR CLIMATE ACTION

Despite both the considerable amount of climate change research made available in the past thirty years and evidence that decision-makers at the local and resource management level (for example, agriculture, water and urban planning) are actively seeking to increase their climate information uptake, there is a persistent gap between knowledge production and use (Maria Carmen Lemos, 2012). Communication between climate scientists and societal sectors thus needs to achieve sensible and efficient action; how to achieve that goal has been and continues to be subject of research (Moser et al., 2016).

Maria Carmen Lemos (2012) acknowledged two main issues creating a "climate information usability gap":

- researchers assume the information they produce is useful because they do not understand the decision-making processes of their intended users;
- users have unrealistic expectations of, or misunderstand how, existing information pertains to their decision making.

In both cases, intrinsically relevant information remains "on the shelf" (Newsom et al., 2016).

Dilling et al., 2011 reviewed empirical evidence on climate science use to identify factors that constrain or foster usability. They found that climate science usability is a function both of the process of scientific knowledge production itself and of the context of potential use. They have also identified that nearly every case of successful use of climate knowledge involved some kind of interaction and iteration between knowledge producers and users (a good example is given by (Allen, 2013). In the literature review on communication gaps conducted for the present report, these two aspects – context of potential use and the process of scientific knowledge production (in interaction with the users or not) – were the most frequently identified factors hindering or fostering the use of climate data and are therefore are here analysed.

Maria Carmen Lemos (2012) described how information moves from useful to usable, and identified concrete actions to improve usability focused on the relation between producers and users of climate data and information. Like Moser (2010) they favour audience-specific use of communication channels for 'retail communication' over mass communication that speaks to no one. Both recognize however the difficulties and challenges in implementing such a model that need to be addressed in future research. One challenge is the critical mismatch between the size of the producer and user communities; the growing demand for climate information can "critically outstrip the ability of producers to establish highly interactive relationships to increase usability" (Maria Carmen Lemos, 2012). Another challenge is that, in practice, human, organizational and material limitations constrain both sides of the science–policy interface.

These findings were further confirmed by Newsom et al. (2016) experience in engaging in a climate-related political process (in the specific case, the implementation of legislation to reduce GHG emissions in Washington State). Their role was to "aggregate and distil published scientific and economic literature…about projected impacts of a suite of potential carbon reduction policies". Witnessing the "politically charged" process as it unveiled Newsom et al. (2016) perceived "the greatest obstacle for climate scientists attempting to conduct research relevant to policymakers: politicians cannot easily relate the most robust projections of future climate to local impacts". They move on to conclude that the scientific community could greatly increase the usefulness of its science by embracing research from economic, social, and psychological sciences to create more policy-relevant research (a good example of such interdisciplinary approach is given by DeLorme et al. (2016). Newsom et al. (2016) argue that conveying the impacts of climate change using societally relevant variables and scales would enable decision-makers to make more informed policy decisions. As a contribution to closing this usability gap, they suggest broadening the climate-science training of graduate students to include education on the uses of climate information outside of academic settings. This would inform and motivate new research directions and also enable students to make informed choices about how to approach their research and build their skillset. Institutionalized pathways for engaging with policymakers would serve students who aim to pursue research oriented for decision making and are interested in creating ties outside of academia. However the implementation of such solutions requires both funding and institutional resources.

Finally, addressing the details of policies for usable science means we need to examine how the process of science works and whether it is conducive to fostering usable science. Attention to the process of selecting and conducting projects, including the flexibility of the research agenda and of the research team can improve the responsiveness of research to user needs. Also of critical importance are the longevity and continuity of research projects. Without considering how science policies enable or constrain the production of usable science, climate research programs will likely miss further opportunities to more effectively support climate-related decision making (Dilling 2011). There is therefore a need to rethink the ways in which applied research programmes are designed to produce usable climate information to meet societal risk and adaptive management needs (Maria Carmen Lemos, 2012).

On the other side of the knowledge information gap, users might ignore data if they have limited understanding or unrealistic expectations of how it relates to their decision-making (Maria Carmen Lemos, 2012). Users won't use information if they don't perceive information as relevant, regardless of its content. In the specific case of climate change mitigation and adaptation, political decision-makers might also disregard climate projections, or perceive them to be irrelevant, because these projections involve timescales that extend far beyond their shorter-term priorities. Maria Carmen Lemos (2012) suggests the need for policy change to increase the range of incentives for the use of climate information and the need to build and sustain capacity for facilitating use.

Lorenz (2017) looked at the question of usability of future climate projections and concluded that reasons for not using them could also be found in regulations around the planning processes, and the discussions of uncertainties associated with climate projections. A central part of their conclusions lays on the understanding of the wider setting, and possibilities to act upon the knowledge within the political and economic constraints within which users act. "A more nuanced understanding of the 'what can be done' can be achieved by looking beyond the immediate institutional context within which users and producers interact and looking outwards to the wider setting and legal and regulatory system within which they are placed" (Lorenz, 2017).

Dilling and Lemos (2011) recognize that connecting or co-producing scientific knowledge with users will not happen automatically; rather a concerted effort to own the problem of producing usable science is needed. Ownership of the problem of creating usable science rests both on scientific organizations (producers) and those organizations that might benefit from the knowledge produced (users). The authors identify a wide variety of institutional arrangements and mechanisms, requiring different degrees of capacity and resources that can help better connect scientific knowledge to users. These range from an embedded expert within a user organization to boundary organizations that both carry out research and mediate between the world of science and users.

More recently, Ernst et al. (2019) have sought to understand the factors hindering the development of effective climate services for adaptation decision-making by examining the production of climate services in Sweden. They have identified constraints related to the production and dissemination of actionable information and stakeholder engagement, as well as funding, professional, and institutional constraints. They conclude that to produce widespread actionable information, climate service producers and institutions must change in order to recognize, reward, support, and pursue methods that enable the production and effective dissemination of climate information services. This can only be done with a combination of adequate funding, staff, guidance and support. The client's business culture, condition and position in its own market or sector are all likely to be just as important in deciding the take up of climate services. However, collaboration and communication between users, service providers and scientists is time consuming, therefore Ernst et al. (2019) expect that a separate specialist climate service community to that of climate researchers might be expected to grow to overcome these barriers.

Extreme type	**Current climate trends in observations or models**	**Future trends**	**Level of understanding and knowledge gaps**
Precipitation	No clear trend can be identified for extreme daily and sub-daily precipitation	Significant increases are projected by several regional climate model generations, for different definitions of extreme precipitation at daily and sub-daily scales. Increases can be expected already for the next decades, and exacerbated toward the end of the century.	Large interannual variability hampers trend analysis for past and present periods. Climate models with parameterized convection, i.e. resolution coarser than 1 km, are not well suited for analysis of sub-daily extremes.
Snow	The snow season has shortened	The snow season is expected to shorten further.	More research is need on the impact of reduced snow volume on tourism.
Floods	Trends in extreme floods range from no significant trend due to large natural variability, to significant increases, depending on geographical region. The main observed trend of flood occurrence is of an earlier spring flow in snow-dominated catchments. Extreme floods at 100 and 200-year return periods in historical climate show general increases over Sweden, except for snowmelt dominated parts in the north of Sweden and in north-west Svealand.	There is no single response to climate change for all catchments. Instead, catchment characteristics can cause distinctly different responses. The main consistent changes are, as in observed trends, a change to earlier snowmelt induced streamflow peak and a general shift from a snowmelt to a rainfall dominated regime mostly in autumn and winter. For all Fenno-Scandinavia the situation is diverse, with (i) a large area that is expected to have less intense snowmelt floods, occurring earlier in spring except and (ii) the southern and coastal areas of Fenno-Scandinavia where an increase of rain-fed flood magnitude is projected.	Hydrological catchment characteristics affect the vulnerability for floods. A knowledge gap is seen in a missing mapping of catchment areas. Also, more research is needed for quantification of different mechanisms linking evaporation, evapotranspiration and precipitation and their representation in models, for Swedish conditions, and on the impact on future projections.
Droughts	Trends are difficult to quantify. For Northern Europe, a slight positive trend is found recently, while earlier studies show a stronger significant increase in frequency.	A decrease of water supply is expected in large parts of southern Sweden, mainly due to the fact that plants consume more water in a warmer climate. A decrease in the frequency and severity of meteorological droughts can be expected over northern Europe and Sweden. With regard to soil-drought, the biggest changes are expected in Skåne and in areas around Lake Vänern and Vättern, with more than 60 more days of drought per year, until the year 2100. In snow-dominated regions, where droughts typically occur in winter, river flow droughts are projected to become less severe because a lower fraction of precipitation will fall as snow in warmer winters.	Further investigation is needed on a regional scale since the results have implications for how we interpret the impact of global warming on the hydrological cycle and its extremes.

Extreme type	Current climate trends in observations or models	Future trends	Level of understanding and knowledge gaps
Wind	Calculated geostrophic winds (mean and extremes) show mainly decadal scale variations. No clear-cut indication of a trend in geostrophic winds over Sweden is found. Direct observation of windstorm location, frequency and intensity have shown considerable decadal variability over the past century, such that no significant long-term trends are apparent. There is no observational evidence for any long-term trend towards a more severe wind climate. At the North Atlantic/North European scale, reanalyses and climate models driven by reanalyses predominantly indicate an increasing trend of mean and extremes during the last four to six decades, but there are significant uncertainties in this conclusion.	Previous reviews based on the, at the time, small number of available studies of the projected future of Scandinavian/Baltic wind climate indicate a reduction in number of windstorms but an increase in intensity. A number of more recent studies, focusing on relevant atmospheric processes, suggest a future increase in regional and local wind extremes and storminess in the region. But it is still too early to draw any conclusion whether this means an increase in maximum intensity or more frequent windstorms.	Due to natural variations, trend detection is currently rarely possible. Improvements are expected from extension of high quality time series, and from climate model simulations in very high resolution, which could expose extreme conditions and associated trends better than recent methods.
Heat waves and cold snaps	Daily summer maximum temperature has increased with 1.7oC from 1880 to 2005 in Scandinavia Since 1961 there is a pronounced increase in warm extremes in most sites studied, including Fennoscandia For Fennoscandia, the number and intensity of cold spells in winter have been found to decrease over the time period 1979-2013 On a European scale, the Probability of a heat wave like the one in 2003 in Europe has more than doubled because of anthropogenic influences	In Fenno-Scandinavia local summer time maximum temperature is projected to increase in about the same way as the corresponding mean temperature regardless of emission scenario Regional climate models project an increase in amplitude, frequency and duration of heat waves for Europe. The summer maximum temperature with a repeat period of 20 years between 1971-2000, may in the end of the century occur every 3-4 years in northern Europe, while wintertime minimum temperatures may become rare and only occur every century or less. On a European scale, the probability of a heat-wave such as in 2003 will increase in the future so that it may occur at least once in a 30 year period. The probability scales with the emission scenario. Extremes associated with cold temperatures are projected to decrease notably at high latitudes.	There does not seem to be any study on heat wave trends in Northern Europe.
Local extremes related to convective systems - hailstorms, thunderstorms, and tornadoes	No reliable information about trends exists, due to missing data, too short time series, underreporting and changes in the reporting routines and systems.	A general limitation in assessing changes in these phenomena is the capabilities of climate models to represent them in a realistic way. Recent development of high-resolution regional climate models have shown significant differences relative to coarser scale models for precipitation related to convective precipitation, but results from such experiments are still missing for most areas.	Further development and application of very high resolution, convection permitting models promises to better represent changes of convective systems on the km and smaller scales
Ice storms	In Sweden severe freezing rain events are uncommon. During the period 2001-2017 only one of more than 100 issued icing and freezing rain watches was a level 2 event, on 19 December 2017, for mid and north Norrland (SMHI 2017). Ice storms are much less frequent and severe in south Sweden compared to in North America. Trends cannot be identified due to short time series in relation to the scarceness of events.	Studies about future ice storm events are missing. Therefore there is no indication about ice storm frequency or intensity in Fennoscandia under the conditions of a warmer climate.	For Sweden and Europe a consolidated climatology of severe icing events, whether of ice storms proper only or including less intensive events, has yet to be compiled. Studies about future ice storm events are completely missing.

Table 6.1: Different extreme types, state of knowledge for recent and future climate as inferred from section 6, and knowledge gaps.

7. SUMMARY AND CONCLUSIONS FOR STAKEHOLDERS AND CLIMATE SCIENTISTS

With a global view, the IPCC report on "Global Warming of 1.5 °C" concludes that "robust global differences in temperature means and extremes are expected if global warming reaches 1.5°C versus 2°C above the pre-industrial levels (high confidence)". This is confirming evidence that certain climate extremes are changing with increasing global warming to amplitudes and return frequencies beyond recent experience (section 1 and 3).

In this knowledge synthesis, global scale research results on climate extremes have been collated, interpreted and refined with a focus on Sweden. Focus areas in this synthesis have been strongly influenced by the advisory board, as described in section 2. We review the knowledge situation about climate extremes with respect to occurrence of past and present extremes (section 3), possible future changes in response to increasing levels of atmospheric greenhouse gas concentrations (section 3), the impacts of climate extremes on society (section 4), possible ways to communicate changing extremes and the need for local and sector-dependent adaptation (section 5). We also collect gaps in the existing research (section 6).

With extreme conditions beyond recent or present experience, mankind's level of preparedness is challenged, and so is the task to adapt to new conditions (section 2 and 5). Adaptation measures need to be related to the impact potential and the risk management needs to include a resilience analysis for the respective societal sector. This synthesis provides methods and examples to facilitate translation of impact potential to options for climate change adaptation that could be applied in Sweden. It even provides insights in the needs to further quantify extremes in the climate system for choosing among alternative mitigation pathways, in order to judge consequences and risks of mitigation choices and mitigation timing on regional and national levels.

Another aspect in the societal discourse on climate change is the potential effect of climate extremes on the perceived urgency of adaptation measures. Extreme events lead to illustration of society's vulnerability and might overcome barriers to adaptation (Travis, 2014). This theoretical effect is however not realized in the majority of cases. For the case of the USA, even the most-extreme events do not necessarily yield significant adaptation. For the case of Sweden, we can note that the anomalously warm summer 2018 in Northern Europe triggered questions about attribution of extreme events to climate change and about the urgency of adaptation and mitigation options.

Trends for extreme events in the climate system in Sweden and Fenno-Scandinavia are described in section 3 and summarized in a condensed table 1 in section 6. Across many extreme variables, the available information is not sufficient to identify clear trends in recent decades. This is the case for precipitation, snow, floods, hailstorms, thunderstorms, tornadoes and ice storms. Droughts show at least a slight increasing trend in frequency. Extreme winds show increasing extremes only on the North Atlantic/Northern Europe scale with no significant signal for Sweden only. Among the variables considered here, only heat waves and cold snaps can be associated with clear observable trends. Maximum temperatures during summer are increasing and the number and intensity of cold spells in winter are decreasing. This knowledge situation can largely be explained by strong variability (on the scale of years and decades) and rather short observational records which make it difficult to identify long term trends in the extremes. Once the geographical area of consideration is extended from Sweden to a larger domain, significant trends can be found (for droughts and wind extremes). Even if no clear trends can be found for many variables, societal sectors might still become more vulnerable due to socio-economic developments independent of climate change.

Future trends of extreme conditions for Sweden rely on regional and global climate model projections that are driven by assumptions on possible future emissions. Already for the coming decades, significant increases in extreme precipitation can be expected. Extreme floods at 100 and 200 year return periods during recent climate can be expected to occur more often in most areas in Sweden, with the exception of snowmelt dominated parts in Northern Sweden and in North-West Svealand. Concerning wind extremes, the intensity is expected to increase, while the development of the number of windstorms is unclear. Heat waves are expected to increase in about the same way as the corresponding mean temperature regardless of emission scenario. No clear indication exists for the future of ice storms and local convection-scale extreme events such as hail storms, thunderstorms and tornadoes in Sweden, due to limitations in many climate models and due to so far incomplete analysis of results from new convection permitting models.

Most of the considered extreme variables show an increase in extreme conditions, with the exception of cold extremes. However, for many variables it remains rather unclear how this outcome is affected by the choice of emission scenario and possible mitigation measures. Existing studies often do not cover a broad range of scenario options.

Given the growing policy relevance of mitigation measures and options, we draw the conclusion that a more detailed exploration of the effects of choosing different emission pathways on climate extremes is needed to better estimate the consequences of political decisions on a global level. Also, better estimates of the effort of climate change adaptation will be possible. Given recent progress in convection resolving climate modelling with increased realism in extreme features, an updated set of high resolution regional climate projections would be most helpful for decision making in Sweden.

The science field of attribution of extreme climate events has gained momentum due to ongoing development of methods for local attribution, involving climate models in addition of observational data. Results allow quantifying the probability of an event with and without manmade climate change. The potential use of event attribution is a better understanding of the physical mechanisms involved and improved possibilities to access the needs of climate change adaptation. Attribution of extreme events also served the frequent public request to understand the causality of such events.

In earlier reports no distinction has been made between impacts associated with changes in average climate and those impacts associated with climate extremes. In this report we are highlighting sectoral impacts associated with climate extremes. Section 4 gives an overview for a range of sectors. Impacts depend naturally very much on the respective sector, so that conclusions need to be drawn for the respective sector only. Impacts of extremes on society are concerning many sectors such as water supply, sewerage, technical distribution systems, transport and communication, forestry, agriculture, health, and buildings including their cultural heritage.

Climate and weather extremes enter the minds and memories of a broad population including decision makers, often as an unwelcome message about climate change. On a professional level, decision makers with a local or national view need to adjust adaptation measures to the needs of the respective sector and geographical area. In good practise cases, adaptation work can be coordinated with other benefits such as disaster risk management, urban renewal, conservation, innovation or economic development. To enable decision makers for that task, communication strategies need to be developed. Several examples are collected in section 5. The communication of scientific information to non-specialized audiences is growing into combined demand-driven and science-informed methods with 2-way dialog being vital. Examples have often used an approach including joint work between societal actors and researchers, in order to produce information which is manageable, useful and understandable for decision-making and planning. It is generally found that articulation of scientific linkages between climate and events (attribution), accurate reporting of the scientific knowledge and co-development can lead to more serious planning to adapt to changes, and more relevant action on climate change.

With today's knowledge about climate extremes (and mean changes) in Sweden and ongoing and coming trends, a basis exists for decision making with respect to climate change adaptation. Deficiencies and further development potential are described in section 6. In summary, substantial gaps exist in our knowledge to reliably represent the full climatology of extreme events, regarding quality and density of observations, regarding climate simulation system's abilities, regarding the potential for future changes of extremes, and with respect to exposure, vulnerability and related impacts on societal sectors. It is worth to highlight the potential of convection-permitting regional climate models that allow for a clear step to much improved statistics of e.g. extreme wind and precipitation events including cloudbursts. Those models also promise to improving the ability to cover compound events and to better serve the needs of climate change adaptation on local level, and to better judge the local consequences of alternative global mitigations choices and temperature target levels.

APPENDIX

CLIMATE EXTREMES FOR SWEDEN

State of knowledge and implications for adaptation and mitigation

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There is clear evidence that climate extremes are changing in a way that goes beyond our experience and adaptation level. The consequences of weather and climate extremes can be huge, and hence, there are important future planning decisions in need of science-informed climate extreme services.

In the project *Climate extremes for Sweden*, funded by FORMAS during 2018 and coordinated by SMHI, the goal is to produce and communicate a condensed and balanced exposition of available information concerning recent and possible future climate extremes and to identify relevant knowledge gaps. The outcome will be a knowledge synthesis which primarily target Swedish stakeholders from local to national level.

Collecting information on climate extremes in Sweden

The synthesis will be based on a Rapid Evidence Assessment as the method to assemble literature within the scope of climate extremes in Sweden.

The Rapid Evidence Assessment includes a structured, step-wise methodology to comprehensively collate, critically appraise and synthesize existing research evidence (traditional academic and grey literature), following systematic review methodology but with components of the process simplified or omitted to produce information within the limited project time of a year.

The information we use are extracted from:

- Peer-reviewed scientific literature on the climate extremes
- The expertise from stakeholders – the users perspectives
- Other literature, so called grey literature, related to extremes

In dialogue with expertise from society

The advisory board for this synthesis consist of professionals from a selection of sectors and knowledge backgrounds. Their input has been vital to the project set-up and progress. A big thank you to:

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Some of our findings for the future so far – project is ongoing

Cloudbursts

Theory predicts an increase in cloudburst intensity of about 7 to 14% per degree C. The lower end of the increase is generally supported by current state-of-the-art models.

However, the results are uncertain because these models are not resolving the core physical processes sufficiently. The emerging paradigm of high resolution models show both higher and lower increases.

Floods

The impact of climate change has diverse impacts across the country, with a general increase in floods in the north, whereas the impact is weaker or even a decrease in the south. This is due to opposing effects of increasing precipitation which is offset by increasing evaporation.

The main consistent changes are, as in observed trends, a change to an earlier snowmelt induced streamflow peak and a general shift from a snowmelt to a rainfall dominated regime.

Further changes include a change to a more pluvial regime with larger impacts on autumn and winter floods compared to the current conditions.

Windstorms

Despite extensive scientific literature and very active research there is not yet a conclusive picture regarding future trends in windstorms over Scandinavia. Datasets from different observational and modelling studies do not agree with respect to the sign of trends

SMHI

Welcome to add your comments here!

Which of these climate extremes and impacts are you most concerned about, for Sweden?

Climate extreme		Climate extreme	
Cloudbursts		Droughts	
Floods		Cold spells	
Windstorms		Sea level extremes	
Heat waves		Landslides	
Other			

Would you like to share an example where an organisation, company or municipality successfully has dealt with a climate extreme?

Would you like to share your best sources of climate infomation that you use in your work, or that you have seen being used?

Figure A.1: Poster presented at the 5th Nordic Conference on Climate Change Adaptation, October 23-25 2018, Norrköping, Sweden

Name	**Provide**	**URL**	**Description of content**
Klimatanpassningsportalen	Knowledge Centre for Adaptation to Climate Change @ SMHI (Sweden)	http://www.klimatanpassning.se/atgarda/lar-av-andra/anpassningsexempel In English: http://www.klimatanpassning.se/en/cases	Searchable database with a number of cases of adaptation organized by categories such as agriculture, animal husbandry, biodiversity, buildings, cultural heritage, ecosystem services, erosion, flooding, forestry, health, heat waves, snow, storm water, tourism and urban planning. The Swedish version lists 70 cases, and the English version 50 cases (as of March 2019), and 61 were categorised in English.
Climate-Adapt	European Environment Agency	https://climate-adapt.eea.europa.eu/	The database includes 90 case studies (as of March 2019), classified by adaptation sector, climate impacts, transnational regions, adaptation elements and countries.
Klimatilpasning	Ministry of the Environment and Food of Denmark / Environmental Protection Agency	https://en.klimatilpasning.dk/cases/ In English: https://www.klimatilpasning.dk/cases-overview	Adaptation cases in a searchable database including 64 cases in danish, and 59 cases in English (as of March 2019), classified by challenges, themes, area type, solution and financing.
ClimateGuide.fi	Finnish Meteorological Institute, the Finnish Environment Institute (SYKE) and Aalto University	http://ilmasto-opas.fi/en/	Collection of adaptation solutions implemented by finish municipalities to mitigate and adapt to climate change. Solutions are only available in Finnish (as of March 2019).
Klimatilpasning (The Norwegian Climate Change Adaptation Portal)	Norwegian Environment Agency	http://www.klimatilpasning.no/eksempler/	The portal is intended to support the society in Norway in preparing for the consequences of climate change. It offers information about ongoing work on climate change adaptation, lessons learned and relevant research, developments and publications. Includes 16 examples in Norwegian (as of March 2019).
Kompas-Tatenbank	Umwelt Bundesamt (Environment Federal Office, Germany)	https://www.umweltbundesamt.de/themen/klima-energie/klimafolgen-anpassung/werkzeuge-der-anpassung/tatenbank	More than 100 examples, searchable by sector, climate category (extreme rainfalls, heatwaves, high water, higher average temperatures, sea level rise, low water, dry periods, changing rain patterns, wind- and storm damage and others), measures support system and state. The cases are written in German.
UKCIP	Environmental Change Institute at the University of Oxford (UK)	https://ukcip.ouce.ox.ac.uk/case-studies/	An archive of adaptation case studies to find out how organisations are planning for and adapting to climate change. The studies are based in a range of sectors or climate risk (coastal impacts, cold weather, drought, flooding, heatwave and wind damage) and geographical areas.
Panorama – Solutions for a Healthey Planet	GIZ (Deutsche Gesellschaft fur Internationale Zusammenarbeit, Germany)	https://panorama.solutions/en/portal/ecosystem-based-adaptation	Documents and promotes examples of inspiring, replicable solutions across a range of conservation and sustainable development topics, enabling cross-sectoral learning. Solutions are searchable under 4 criteria: region of the world, ecosystem (marine, freshwater, forest ...), theme (climate change, biodiversity, financing,...) and challenge (climate, economic, social,...).
CAKE - Climate Adaptation Knowledge Exchange	EcoAdapt (USA)	https://www.cakex.org/	CAKE's case studies database provides access to information about on-the-ground climate change adaptation projects. Through interviews and surveys, EcoAdapt synthesizes how people are preparing for or responding to climate change, mostly in the US. Case studies are searchable under 6 criteria: scale of project, sector addressed, impacts, region, adaptation phase and habitat.
Circle-2 Adaptation Inspiration Book	EU-funded project CIRCLE-2, Portugal	https://climate-adapt.eea.europa.eu/metadata/publications/circle-2-adaptation-inspiration-book	A collection of 22 implemented cases of local climate change adaptation to inspire European citizens.
BASE Adaptation Inspiration Book	EU-funded project BASE, Denmark	https://base-adaptation.eu/sites/default/files/BASE%20Inspiration%20Book.pdf	A collection of 23 cases from Europe about adaptation to climate change, as a follow up of the CIRCLE-2 Adaptation Inspiration Book.
GRaBS Adaptation Action Planning Toolkit	GRaBS Interreg IV funded project, UK	http://www.ppgis.manchester.ac.uk/grabs/casestudies.php	A database of case studies to showcase climate change adaptation approaches, with a particular emphasis on those relating to green and blue infrastructure. Focus on extreme temperatures and flooding. Malmö was one of the project partners.
The European NWRM (Natural Water Retention Measures) platform	Office International de l'Eau, France	http://nwrm.eu/list-of-all-case-studies	The platform gathers information on NWRM at EU level. NWRM are green infrastructures applied to the water sector, which allow achieving and maintaining healthy water ecosystems, and offer multiple benefits. Includes a catalogue of case studies collected using a common template.
Climate Services for Health Fundamentals and Case Studies for improving public health decision-making in a new climate	WMO	https://public.wmo.int/en/resources/library/climate-services-health-case-studies	The Climate Services for Health Case Study Project showcases 40 examples to help better understand: how climate information can help health decision-making; what climate products and services for health exist; the types of information products which are commonly developed; fundamental components that should be addressed during the co-development of climate services; and ways to trouble shoot common problems encountered. 40 case studies are featured for illustration.

Table A.1: Websites displaying cases or good examples related to adaptation to climate change

GLOSSARY

Here we provide a glossary in a language expected to be understandable by an interested audience outside the science community, without ambition for completeness. Related glossaries exist already, for example in the SREX report.

Convective precipitation
Convective precipitation is defined as a type of precipitation that occurs when air rises vertically through the mechanism of convection, i.e. through vertical movement due to heating of near surface air under the conditions of an unstable atmosphere. Convection in moist air is connected to cloud formation that in turn leads to so called convective rain that falls over a rather short time.

Clausius-Clapeyron relation
The Clausius-Clapeyron relation describes the relationship between two phases in a substance as a function of temperature. In meteorology, this is mainly applicable to the gaseous and liquid phases of water. The Clausius-Clapeyron relation predicts an about 7% increase in the water holding capacity of air with a 1 degree increase in temperature, for temperatures around 20 degrees Celsius.

Cyclone
A cyclone is a large scale air mass that rotates around a strong center of low atmospheric pressure. In the northern hemisphere the rotation is counterclockwise. Because cyclonic circulation and relative low atmospheric pressure usually coexist, in common practice the terms cyclone and low are used interchangeably. Also, because cyclones are nearly always accompanied by inclement (often destructive) weather, they are frequently referred to simply as storms. Northern Europe and Scandinavia are affected by mid-latitude cyclones (aka extra-tropical cyclones). In intense mid-latitude cyclones the wind speed may reach well above hurricane force, 32 m s-1, but the weather system is still not a hurricane (cf. hurricane.) Such high wind speeds are rare over inland, except temporarily in gusts. [Based on the American Meteorological Society Glossary <http://glossary.ametsoc.org/wiki/Cyclone> (accessed 2019-04-03), and Wikipedia <https://en.wikipedia.org/wiki/Cyclone> (accessed 2019-04-03)]

Cyclone track
The path followed by an individual meteorological phenomenon, for example, a center of low atmospheric pressure, a severe thunderstorm, a tornado. Cf. storm track.

Climate model
Climate models or Earth System Models (ESMs) represent advanced and complex descriptions of the Earth's atmosphere, ocean, and land surface. They describe the global climate system through a combination of coupled physical-mathematical equations. ESMs add biogeochemical cycles. The models provide three-dimensional climate variables, such as temperature, precipitation and wind. Climate models are routinely used to simulate the earth's climate both in the past and into the future. Results are utilized to estimate effects and impact of possible future climate including uncertainty.

Climate scenarios
Climate scenarios describe alternative emission pathways into the future. They are labeled Representative Concentration Pathway (RCP), combined with a number (2.6 - 8.5) corresponding to the greenhouse gas' radiative effects on the atmosphere by the year 2100. Higher numbers mean higher emissions and higher effect.

Ensemble
Climate models are often run in parallel experiments with slightly differing initial conditions, but with otherwise identical setups. Due to natural variability, that exists in nature and in climate models, these parallel runs provide a complete range of amplitudes of that variability, that relates to the uncertainty of a prediction or climate change projection.

GCM
Global climate model

Geostrophic wind
The geostrophic wind is a good approximation of the real large scale atmospheric flow. It is often used as a substitute for wind observations to describe the wind climate because it is simple to calculate from pressure observations, for which there exists high quality long observational data series. The forces characterizing the geostrophic atmospheric flow is the pressure gradient force which is balanced by the Coriolis force.

Hurricane
A tropical cyclone with 1-min average surface (10 m) winds in excess of 32 m s-1 (64 knots) in the Western Hemisphere (North Atlantic Ocean, Caribbean Sea, Gulf of Mexico, and in the eastern and central North Pacific east of the date line). Note that a hurricane is a completely different meteorological phenomenon than an intense mid-latitude cyclone yielding hurricane force winds. [Based on the American Meteorological Society Glossary <http://glossary.ametsoc.org/wiki/Hurricane> (accessed 2019-04-03)]

North Atlantic Oscillation (NAO)
The North Atlantic Oscillation is a large scale atmospheric pattern that consists of opposing variations of barometric pressure near Iceland and near the Azores. It corresponds to fluctuations in the strength of the main westerly winds across the Atlantic into Europe, and thus to fluctuations in the embedded cyclones with their associated frontal systems. [based on IPCC SREX Glossary (rd_SREX_field2012)]

RCM
Regional climate model, featuring higher resolution compared to a GCM (Global climate model)

RCP
Representative concentration pathways, a set of four pathways developed for the climate modeling community as a basis for modeling experiments. They consist of a comprehensive data set with high spatial and sectoral resolutions for the period extending to 2100, including land use and emissions of air pollutants and greenhouse gases per sector.

Resolution
Climate data from observations and from climate models often are provided on a geographical grid with data points at (often) regular distances or locations. The distance between the data points is referred to as data resolution.

Scales
Weather phenomena vary at all scales of space and time. The conceptual spatial scale can be expressed in many ways, and there are numerous alternative definitions of the terminology. For the purpose of this report we identify the following broad categories, with a rough indication in kilometers. Global scale includes also phenomena confined to one hemisphere only. Large scale (5000 to 1000 km), or continental scale, are phenomena of an extent that could influence entire Europe, eg. large mid-latitude cyclones or cyclone trains over the North Atlantic. Regional scale refers to 1000 – 100 km, and the local scale is often considered to cover 500 – 1 km.

Storm
Any disturbed state of the atmosphere, especially as affecting the earth's surface, implying inclement and possibly destructive weather. For example, hailstorm, rainstorm, snowstorm, windstorm. The Swedish word ”storm” is understood as a windstorm having wind speed above 24.5 m/s. [Based on the American Meteorological Society Glossary <http://glossary.ametsoc.org/wiki/Storm> (accessed 2019-04-03)]

Storm track
A region in which the mid-latitude cyclone activity is statistically and locally most prevalent and intense. In winter the North Atlantic storm track is centered at about 45°N. Cf. cyclone track.

Storminess
This is a general and somewhat vague term for the severity of weather and climate. Thus, it is not not only related to the frequency and intensity of wind storms or the wind climate in general. At the mid-latitudes the storminess is closely related to the frequency and intensity of mid-latitude cyclones.

Time slices
To analyse and compare climate observations or simulations, oftentimes limited time periods are considered due to limited data availability, analysis capacity, or necessity to compare different time periods. The time periods chosen are called time slices and often cover 20-30 years. This choice smoothens out interannual variability, but cannot fully compensate for interdecadal variability.

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