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Climate in Norway 2100

– a knowledge base for climate adaptation

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Abstract

This report is a condensed English version of the Norwegian report "Klima i Norge 2100", published in 2015 to provide an updated scientific basis for climate adaptation in Norway. The focus is on future climate, but the causes of climate change and variability, as well as the development of the climate in Norway since the last glaciation, and particularly during the instrumental age, are briefly described. Projected climate change through the 21st century is described under various assumptions for future emissions of greenhouse gases. Most of the estimates are based on global climate projections from the 5th Assessment Report of the IPCC. Emphasis is placed on changes up to the middle and end of the 21st century. Climate projections are influenced by uncertainties, and this topic is thoroughly discussed in the report.

Both versions of the report may be downloaded from the Norwegian Centre for Climate Service's web portal www.klimaservicesenter.no.

Keywords

Climate in Norway, projections, temperature, precipitation, wind, runoff, floods, droughts, snow, glaciers, permafrost, landslides and avalanches, ocean climate, sea ice, sea level

Disciplinary signature

Responsible signature

Contents

Acknowledgements

The present report is a condensed English version of the report "Climate in Norway 2100" (Hanssen-Bauer et al., 2015; in Norwegian). Several institutions contributed to the Norwegian report (the numbers identify the affiliations given in the list of authors):

1. Norwegian Meteorological Institute (MET Norway),
2. Norwegian Water Resources and Energy Directorate (NVE),
3. Uni Research,
4. University of Bergen (UiB),
5. Institute of Marine Research (IMR),
6. Nansen Center (NERSC)
7. Norwegian Mapping Authority (Kartverket).
8. Norwegian Centre for Climate Services (NCCS)
9. Bjerknes Centre for Climate Research

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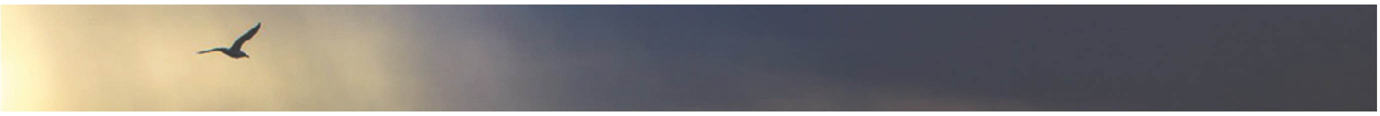
Oslo, May 2017

Inger Hanssen-Bauer



Summary

Main findings

Past, present and future projections for climate in Norway up to year 2100 are presented in this report. The report is meant as a basis for climate adaptation in Norway, and the results have been applied in countyvise "Climate fact sheets". The Norwegian white paper on climate adaptation (Meld. St. 33 (2012–2013)) says that "to be precautionary, the government wants risk assessments of climate change to be based upon the high climate projections". The highest among the scenarios in the latest report from the Intergovernmental Panel for Climate Change (IPCC) is the RCP8.5. Under this scenario, the following changes (given as median values) are estimated in Norway by the end of this century:

- Annual temperature will increase by ca. 4.5 ºC (interval: 3.3 to 6.4 ºC)
- Annual precipitation will increase by ca. 18 % (interval: 7 to 23 %)
- Events with heavy rainfall will be more intense and occur more frequently
- Floods induced by rainfall will increase in magnitude and occur more frequently
- Snowmelt floods will decrease in magnitude and frequency
- In lowland areas, the winter snow cover will often be negligible or non-existent, while snow volumes may increase in some areas in the high mountains
- The number of glaciers will be reduced, and the remaining glaciers will be substantially reduced
- Mean sea level will increase by 15 - 55 cm depending on location along the Norwegian coast

In the event of reduced greenhouse gas emissions (e.g. RCP 4.5 or RCP2.6), the expected changes will be significantly less.

This report includes mainly information on national and annual scale, and mainly for the end of the 21st century. In the Norwegian version "Klima i Norge 2100", a comprehensive Appendix is included; presenting seasonal and annual median, low and high projections for different emission scenarios up to 2031-2060 and 2071-2100, for different regions within Norway, and for several meteorological and hydrological variables. This info is also available on the Norwegian Centre for Climate Services' web portal www.klimaservicesenter.no. The Norwegian as well as this English version of the report are also available there, as well as Climate fact sheets (in Norwegian) for all counties.

Background. This report provides basic information for use in climate adaptation in Norway. The projections for future climate are mainly based on results in the IPCCs fifth assessment report. Essentially, three scenarios for emissions of greenhouse gases are used: "RCP8.5" ("business as usual"); "RCP4.5" (reductions after 2040) and "RCP2.6" (drastic cuts from 2020). The global model results are downscaled and postprocessed. The period 1971-2000 is used as reference period and climate change is estimated up to 2100. Inadequate knowledge of the climate system's sensitivity and of future natural climate variations, and also limitations in the climate models, leads to uncertainties in the projections even under a given emissions scenario. Where sufficient data are available; median, high, and low projections are estimated. The span between the high and low projection includes 80% of the projections (90% for sea level).

Air temperature and derived variables. The mean annual temperature (1971-2000) for Norway was +1.3 °C. Annual temperature has increased by ca. 1 °C from 1900 to 2014, with largest increase in spring and winter. For RCP8.5, the median projection indicates an increase in annual mean temperature for Norway of 4.5 °C (span: 3,3 to 6,4 °C) up to 2071-2100. Largest warming is projected for interior parts of Northern Norway, and smallest for western Norway. The greatest warming is projected for winter, and least warming for the summer season. The median projections are significantly lower for RCP4.5 and RCP2.6 (2.7 and 1.5 °C, respectively). The warming leads to a longer growing season, especially along the coast.

Precipitation. Mean annual precipitation (1971-2000) for Norway is estimated to be 1600 mm, and has increased by ca. 18 % since 1900. The increase was largest in spring and smallest in summer. Intensity and frequency of heavy short-duration rainfall has increased in recent years. The projections show that annual precipitation, number of days with heavy precipitation, and rainfall intensity on such days are expected to increase. For RCP8.5 the median projections for Norway indicate an 18 % increase (span: 7 to 23 %) in annual precipitation towards the end of the century, and a doubling of days with heavy precipitation. Preliminary analyses suggest that rainfall intensity for durations of a few hours may increase by more than 30 %.

Wind. The last 50 years there has been a slight increase in wind velocity that is exceeded in 1% of the time. Projections indicate only very small future changes in average values and large wind speeds.

Runoff. Of the estimated annual precipitation of 1600 mm for Norway, more than 1100 mm goes to runoff, while a little less than 500 mm evaporates. The observed warming has generally led to increased runoff in winter and spring and earlier snowmelt. The median of all projections indicate relatively small change in total annual runoff for Norway for the next 50 years. Towards the end of the century a small increase is projected for RCP8.5. The changes in different seasons are considerably larger, with increased runoff in winter and reduced runoff in the summer season.

Floods. Higher temperatures have led to earlier spring floods. There is no historic trend in the magnitude of floods, but in recent decades there is a tendency to increased frequency of rain floods. The magnitude of rain floods is projected to increase, while meltwater floods will decrease over time. In river systems dominated by snowmeltfloods, a reduction of up to 50% (RCP8.5) is expected in spring floods. In river systems that are dominated by rain floods, the magnitude of floods is projected to increase by up to almost 60% (RCP8.5). More frequent and stronger intense rainfall events may in the future give special challenges in small, steep rivers and in urban areas.

Droughts. An increase is estimated for soil moisture deficit towards the end of the century. This may have implications for e.g. agriculture, forestry, irrigation needs and forest fires.

Snow. The maximum water content of snow on the ground varies from near zero to over 2000 mm. Coastal areas have in average only a few days a year with snow cover, while glacial areas almost always have some snow lying over the summer. Analyzes of historic time series broadly show tendencies to larger snow amounts in the mountains and smaller in the lowlands. The length of the snow season is projected to decrease all over the country, with largest reduction in the lowlands. Most places, reduction is also projected for the maximum snow depth. However, in some high-mountains areas, an increase is indicated for the maximum snow amount.

Glaciers and frozen lakes. Most Norwegian glaciers are now smaller than they have been for hundreds of years. For large glaciers, the projections towards the end of the century indicate a reduction of up to 1/3 of the area and volume they have today. Smaller glaciers will disappear except at the highest altitudes. The period of the year with frozen lakes will be significantly shorter than today, and ice thickness will be reduced. Ice drift on rivers will become more common at higher altitudes and further inland than in the current climate.

Permafost. Permafrost during 1981-2010 covered ca. 6% of the land areas in Norway. Projections indicate that within 2050 most permafrost areas at Finnmarksvidda will have thawed, and that by year 2100 permafrost will only exist at the highest mountains.

Landslides and avalanches. The present data basis is not sufficient to analyse historic trends in avalanches and landslides. Weather triggers certain types of slides and avalanches, and climate change may thus affect their future frequency. In steep terrain, climate change may lead to increased frequency of landslides, debris flows and slush avalanches associated with heavy rainfall. Increased erosion could trigger more quick clay slides. The risk of dry snow avalanches will decrease, while the risk of slush slides will increase, and may occur in areas where they have not occurred previously.

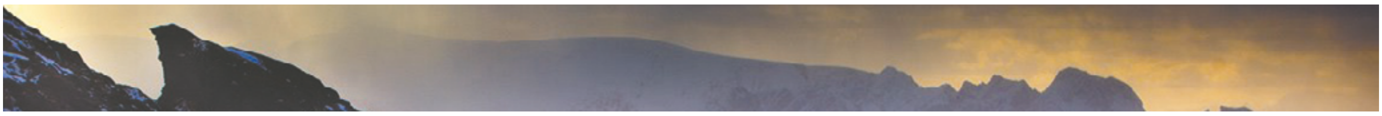
Ocean climate. The ocean climate of the Norwegian Sea and the Barents Sea is largely determined by the inflow of Atlantic water. Downscalings of global climate models indicate a winter warming in Norwegian waters over the next fifty years. A temperature increase of about 1 °C is estimated for the Barents Sea, while somewhat larger increase is estimated for the North Sea. In summer there is a larger spread in results, probably due to different sea-ice extent in the models. A downscaling based on RCP4.5, indicate a weaker warming in summer than winter, especially in the North Sea. Due to increased CO_2 uptake, the pH-value of the ocean surface is estimated to be be reduced by ca. 0.2 from 2000 to 2065.

Sea ice. The observed reduction in Arctic sea ice is one of the most significant signs of climate change in the Arctic. State-of-the-art climate models simulate reduced sea-ice cover and thickness in the Arctic during the later decades, however, a majority of the models show a smaller reduction than observed. For projections under RCP8.5, the nine models in most agreement with observations indicate an “ice-free Arctic” in September 2054–2058. No climate model simulates an ice-free Arctic in winter by 2100.

Sea level. The sea level off the Norwegian coast is calculated to have increased in average by 1.9 mm per year in the period 1960-2010. Projections indicate that most coastal areas will experience rising sea levels. For RCP2.6 the mean projection give a change in sea level in the interval -10 to +30 cm depending on location. For emission scenario RCP4.5 the interval is 0 to +35 cm and for RCP8.5 it is +15 to +55 cm.

Uncertainties and use of projections. Uncertainties in climate projections are related to 1) future anthropogenic emissions, 2) natural climate variations and 3) climate models. The first type of uncertainty is taken into account by using 2-3 emission scenarios. The second and third types of uncertainties are to some degree taken into account by giving intervals based on ensembles of several model calculations. However, these span only a part of the total uncertainty. Thus it can not be ruled out that future climate changes could fall outside the intervals. For use of climate projections in research and management it is thus recommended that relevant scientific communities are contacted.

For the next 10-20 years, natural variations will largely dominate over the “climate signal” resulting from enhanced greenhouse effect. It is therefore recommended that for planning of measures or constructions with a lifetime limited to the next few decades, statistics based on the latest 30 years are used rather than downscaled results from climate model simulations.



1. Introduction

1.1 Rationale and background

The first «Climate in Norway 2100»-report (Hanssen-Bauer et al., 2009; in Norwegian) was published in order to form a common basis for the Norwegian green paper on climate change adaptation (NOU 2010:10). It summarized knowledge of historical climate change in Norway, as well as global and regional scale climate projections that were available at that time. Subsequently, the IPCC issued a new assessment report on the global climate system with updated projections for future climate change (IPCC, 2013). These newer global climate projections have now also been downscaled to regional levels so that new climate projections focusing on Europe are available. Further, a white paper on climate change adaptation has been launched (Meld. St. 33 (2012–2013)).

The second version of «Climate in Norway 2100» (Hanssen-Bauer et al., 2015; in Norwegian), was commissioned by the Norwegian Environment Agency, to provide updated information relevant for climate adaptation in Norway. The report summarizes updated information on the past, present and projected future climate up to year 2100. The future projections are based on different assumptions for greenhouse gas emissions (emission scenarios). Though the climate models are not perfect, they still give a clear picture of the main features of how we expect global warming to turn out in Norway. The present report is a condensed English version of this second Norwegian climate report.

The «Climate in Norway 2100» reports form a basis for climate adaptation in Norway, but they are too comprehensive to be used directly in management and land-use planning in counties and municipalities. Thus, based on information in the second report, 8-page "Climate factsheets" ("Klimaprofiler") have been developed for each county. The Climate factsheets identify the main climate related concerns for each county, and suggests "climate factors" for heavy precipitation, river floods and storm surges based upon projections under emission scenario RCP8.5 (see Ch. 2.1).This high scenario is emphasized because the Norwegian white paper (Meld. St. 33 (2012–2013)) states that "to be precautionary, the government wants risk assessments of climate change to be based upon the high climate projections".

The "Climate in Norway 2100" reports, as well as all "Climate factsheets" may be downloaded from https://klimaservicesenter.no/.

1.2 Climate change and weather variations

Climate change, due to an imbalance in the energy exchange between the Earth and space ("external forcings"), has occurred throughout the Earth's history. Until a few hundred years ago, these changes were mainly due to natural causes, but in recent years human activity has increasingly influenced this energy exchange. According to IPCC (2013), human activity (especially the anthropogenic emissions of greenhouse gases) is the main reason for the observed increase in global temperature since 1950.

In addition to climate changes caused by changes in the external forcings, energy exchanges within the climate system may also lead to variations in the planet's weather patterns. Such variations, which occur naturally in the climate system, can cause very different effects in different regions. It is a challenge to distinguish these effects from changes due to external forcing, and it is often unclear how these variations are affected by global warming.

Because of its high latitude, Norway has a net radiation loss to space. However, large-scale circulation of relatively warmer air and seawater adds energy to our region. Variations in atmospheric and oceanic circulation patterns cause differences in local weather on time scales up to several decades. Changes in these circulation patterns will lead to changes in regional climate for Norway. Examples are e.g. changes in the extent, intensity or paths of cyclones, and changes in volume or heat content in the Norwegian Atlantic current.

Reliable instrumental meteorological data from Norway mostly dates back to about 1860. To reconstruct climate further back in time, indirect (proxy) data are used. It is possible to base such proxies on e.g. tree-rings, seabed and lake sediments, plankton and pollen.

1.3 Planning of buildings and infrastructure with a short lifetime

When planning buildings and infrastructure with a lifetime of 30 years or more, projections for changes in climate and hydrology should always be considered (see Ch. 2). For the next 10-20 years, however, natural variations will largely dominate over the "climate signal" resulting from an enhanced greenhouse effect. For design of measures or constructions with a life time corresponding to this time horizon, it is thus recommended to use updated observations rather than climate projections. The advantages of using statistics based on real observations are believed to outweigh the disadvantages of neglecting the climate change signal for this short time horizon.

In this report, the period 1971-2000 is used as a reference period for atmospheric and hydrological variables. However, for a number of variables, there have been significant changes in recent years. In order to get a better impression of the current climate, we have compared the reference period with the latest thirty years (1985-2014). For short term planning, it is recommended that updated observation records, including recent years, are used.

2. Projections of future climate; - models, methods and data

2.1 Emission scenarios, global climate models and downscaling

The climate projections in this report are derived from global climate models run with different emission scenarios. Unless otherwise stated, the projections are based on results from the Fifth Assessment report by the Intergovernmental Panel on climate change (IPCC, 2013). This report makes use of three of the IPCC emission scenarios, so-called "Representative Concentration Pathways (RCPs)": RCP2.6, RCP4.5, and RCP8.5. In short, RCP2.6 is a scenario requiring drastic global emission reductions throughout the century, starting already before 2020. RCP4.5 implies a slow increase of emissions until 2050 followed by emission reductions. RCP8.5 implies that greenhouse gas emissions will continue to increase. The report only considers air temperature and sea level for the scenario RCP2.6. This is because of the shortage of available downscaled data for this scenario.

Global climate models typically operate on a horizontal grid size of 100x100 km^2, thus they are not fit-for-purpose to resolve meso-scale phenomena that are important for Norway and its climate. Consequently it is necessary to downscale these models. In this report, results from following three methods are presented: (i) Empirical-Statistical Downscaling (ESD), (ii) dynamical downscaling with regional climate models (RCMs), and (iii) adding regional/local adjustments to the global model output. Different method(s) have been used for different variables (see below).

2.2 Atmospheric variables

Atmospheric RCM-simulations were downloaded from CORDEX (Coordinated Regional Climate Downscaling Experiment), more specifically from their Euro-CORDEX initiative (http: //www.euro-cordex.net/). Euro-CORDEX downscales global models for Europe by using regional climate models with spatial resolution of 12x12 or 50x50km^2. Due to the Norwegian topography we have only made use of the finest grid resolution for this report. Ten projections were available for the two scenarios, RCP4.5 and RCP8.5. The 12x12 km^2 daily temperature and precipitation values from the RCM-simulations were then interpolated to a 1x1 km^2 grid and thereafter bias-adjusted (Wong et al. 2016). In addition, the ESD-method was used to project air temperatures for different sub-regions in Norway. A large number of global model simulations (for RCP2.6: 64, for RCP4.5: 107 and RCP8.5: 77) were included (Benestad, 2011) providing additional information regarding uncertainty and representativeness of the RCM-results. The ESD-results also enable comparison between the RCP2.6 projections and those based on RCP4.5 and RCP8.5. An overview of global and regional climate models used in the ESD and RCM downscalings can be found in Appendix A.5.1 in Hanssen-Bauer et al., 2015.

As a consequence of insufficient knowledge about the sensitivity of the climate system, as well as future natural climate variability and limitations in the climate models themselves, all projections are burdened with uncertainty even under a given emission scenario. Therefore median (50th percentile), high (90th percentile), and low (10th percentile) values are estimated. The range between the high and low projection comprises 80 % of the projections, reflecting the uncertainty in the model output. The projections in this report primarily describe changes for two future 30-year periods, namely 2031-2060 and 2071-2100 with 1971-2000 as a reference period.

2.3 Hydrological variables

Hydrological models are used to estimate consequences of changes in atmospheric variables for hydrology. For the results presented in this report, two versions of the hydrological model HBV were used (Beldring et al., 2003; Bergström, 1976): One version performs calculations for the entire country for grid squares of size 1x1 km^2, and one version estimates the water balance in selected river catchments. Input data for the HBV model is daily values of precipitation and temperature, i.e. the post-processed RCM data described in Ch. 2.2. The HBV model is run for all ten available RCM projections for emission scenarios RCP4.5 and RCP8.5, and for the same time periods as temperature and precipitation. For projected runoff, the results are given as a median value with the same range as outlined in Ch. 2.2. Similarly, the main projections periods for hydrological variables are 2031-2060 and 2071-2100, while 1971-2000 is the reference period.

2.4 Oceanographic variables

The ocean's large heat capacity leads to far less temperature variation than in the atmosphere. Using shorter time periods to characterize climate can therefore be justified, and time periods of 10 years are used in this report to characterize ocean climate and compare different periods.

For future development of oceanographic variables, much fewer downscaled model results are available than for the atmosphere. Projections for climate change in the ocean presented in this report are mainly based on dynamic downscaling of global climate model results from the two latest IPCC assessments, for emission scenarios RCP4.5 (IPCC, 2013) and A1B (IPCC, 2007). To include influences from the large-scale ocean circulation properly, the model domain for downscaling cover a substantial area upstream of the Norwegian waters. The oceanic downscaling is performed with the regional ocean model ROMS (Shchepetkin & McWilliams, 2005), with a grid resolution of about 10x10 km^2 in the Nordic Sea and the Barents Sea. The choice of global models for downscaling is based on evaluations of the various models' ability to reproduce observed heat transfer and sea ice extent. The downscaled oceanic area covers the entire Norwegian coast. In addition, some downscaled results from different global and regional models are included for the North Sea and Skagerrak.

2.5 Relative sea level

Changes in sea level are influenced by ocean density and circulation, wind stress, air-sea fluxes and freshwater supply. These processes are included in the IPCC (2013) global model simulations, which form the basis for the projections of sea level given in this report. The reference period is the 20-year period 1986-2005 and the projection period is 2081-2100. Global simulations for the three emission scenarios RCP2.6, RCP4.5 and RCP8.5 are applied. When estimating regional relative sea level, regional effects must also be addressed. Land rise is presently the most important of these in Norway. Detailed information about the sea level model basis is reported in Simpson et al. (2015).

3. Atmospheric variables

3.1 Air temperature and derived variables

3.1.1 Temperature in the pre-instrumental age

To reconstruct pre-instrumental climate, a number of proxy-based indices may be used. The following paragraphs summarise analyses of variations in tree-rings (e.g. Linderholm et al., 2014), seabed (e.g. Eldevik et al., 2014) and lake sediments (e.g. Bjune, 2005), speleothems (Lauritzen and Lundberg, 1999) and glaciers (e.g. Nesje, 2009). These proxies indicate that a cold period named "Younger Dryas" lasted from about 12,800 to 11,700 years ago. The Younger Dryas period marked the end of the last Ice Age, and the beginning of the present interglacial period ("Holocene"). The temperature-rise in the early Holocene was interrupted by short, cool periods; the last of which occurred approximately 8200 years ago (Figure 3.1). Proxy data from land areas, as well as reconstructed sea-surface temperatures, show that the highest summer temperatures in our region occurred between 8,000 and 6,000 years ago. In this period, the summer temperatures were approximately 1.0-1.5 °C higher than during the reference period 1971-2000. After the warm period 6,000 years ago, there was a tendency of gradual decline in summer temperatures, however, with significant fluctuations. This cooling tendency culminated in the so-called "Little Ice Age".

Different studies provide a somewhat different time-frame for the 'Little Ice Age', but in Norway most of the glaciers reached their maximum Late Holocene extent in the mid-18th century (Figure 3.1). This period was characterised by famine, and most temperature estimates suggest that average summer temperatures were around 1°C lower than in the

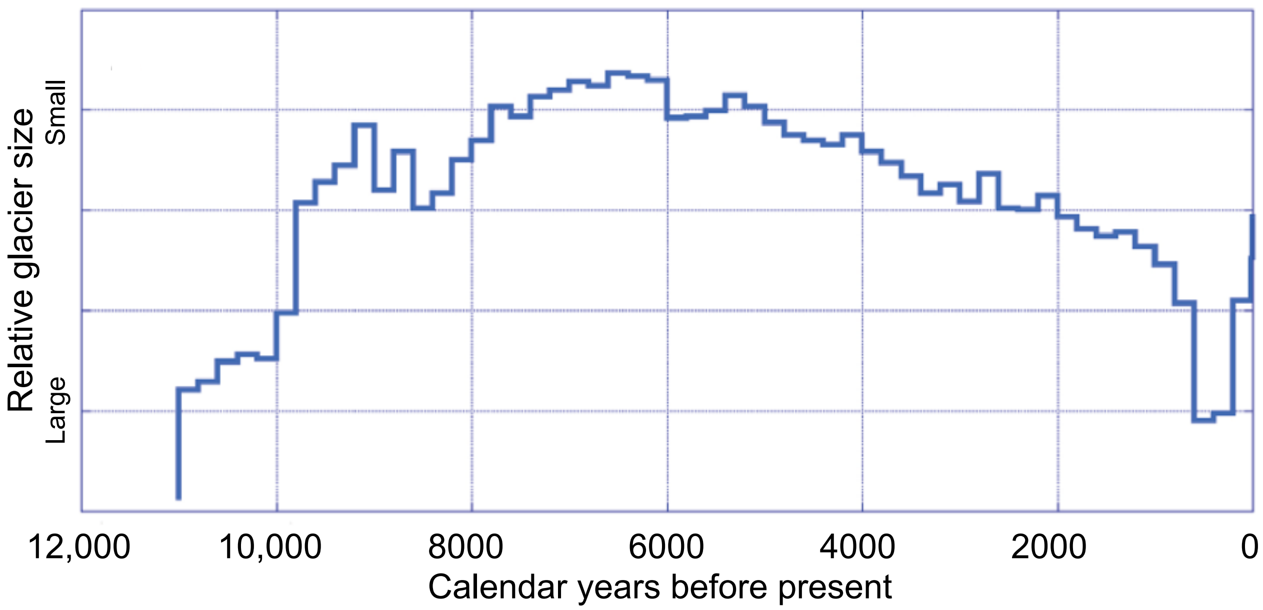


Figure 3.1 Glacier variations in Scandinavia during the last 11,000 years (for details, see Nesje (2009)).

reference period 1971-2000. Figure 3.1 indicates that the fronts of Scandinavian glaciers are now roughly in the same position today as around 2,000 years ago.

The main features of the historical temperature development sketched above are in line with well-known changes in the external climate forcing. In the first part of the Holocene, the Earth was closest to the sun in the Northern Hemisphere summer, whereas at present the Earth is closest to the sun in the northern winter. The Earth's axis also had greater inclination than at present. In early Holocene, high Northern latitudes therefore received 10-12 % more solar radiation in summer than at present. Variations around the decreasing temperature trend during the Late Holocene (pre-industrial) were probably linked to internal climate variability and to natural climate forcing factors (mainly volcanic eruptions and solar activity).

3.1.2 Observed and projected temperatures

The mean annual temperature for the Norwegian mainland during the reference period 1971-2000, is calculated to +1.3 °C. The highest annual temperatures, up to +7 °C, are found along the coast of southern Norway and the lowest in the high mountains with down to -4 °C. From 1900 until 2014 there have been periods of both increasing and decreasing temperatures, but for the past 40 years the increase has been very pronounced (Figure 3.2). As for the global temperature (IPCC, 2013), the warming in Norway since 1900 has occurred in two periods, "the early 20th century warming" with a maximum in the 1930s, and warming during the most recent decades. From 1900 until 1938 the linear trend in annual temperature was +0,32 °C/decade, and from 1976 to 2014 +0,50 °C/decade. Between these two periods of warming, there was a cooling period with a linear decrease between 1938 to 1976 of -0,04 °C/decade.

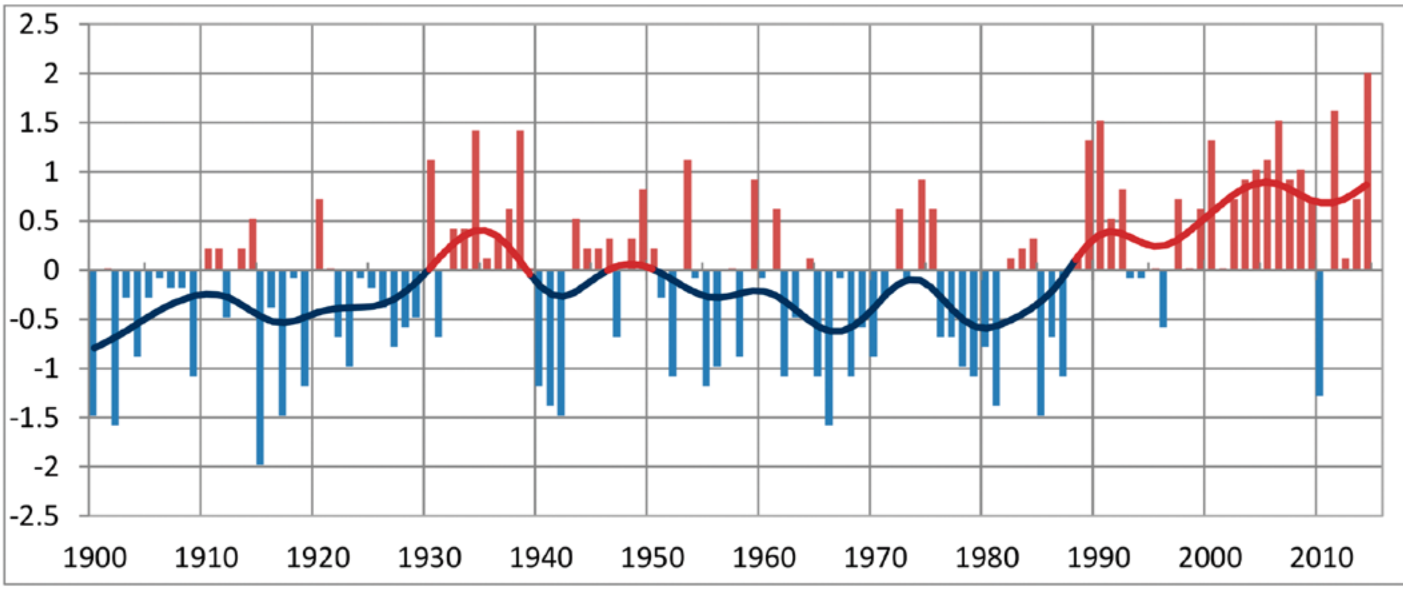


Figure 3.2 Annual temperatures for the Norwegian mainland during 1900–2014. The figure shows deviations (°C) from the mean temperature during the period 1971–2000.

Temperature region:	1	2	3	4	5	6	Norway
Annual	**0,08**	**0,06**	**0,1**	**0,11**	**0,08**	**0,09**	**0,09**
Winter	0,02	0,02	0,08	0,08	-0,03	0,05	0,04
Spring	**0,13**	**0,08**	**0,13**	**0,14**	**0,15**	**0,14**	**0,13**
Summer	0,07	0,05	0,08	0,08	0,08	0,05	0,07
Autumn	**0,08**	**0,07**	**0,11**	**0,12**	**0,09**	**0,11**	**0,09**

Table 3.1 Linear trends (1900-2014) in annual and seasonal temperatures in Norwegian temperature regions (see Figure 3.3a) and for the Norwegian mainland. Trends are expressed as °C per decade, and bold numbers are statistical significant at the 1 %-level (Mann-Kendall non-parametric test).

From 1900 until 2014 the annual mean temperature for the Norwegian mainland increased by approximately 1 °C (Table 3.1), i.e. at about the same level as the global temperature (IPCC, 2013). The largest temperature increase was found in Trøndelag (region 3 in Figure 3.3a) and Nordland/Troms (region 4). The temperature increase for Norway as a whole was greatest in spring and smallest (and not statistically significant) for the winter season (Table 3.1). In all regions the largest warming is found for spring and autumn. For the winter season none of the regions had statistically significant trends in temperature.

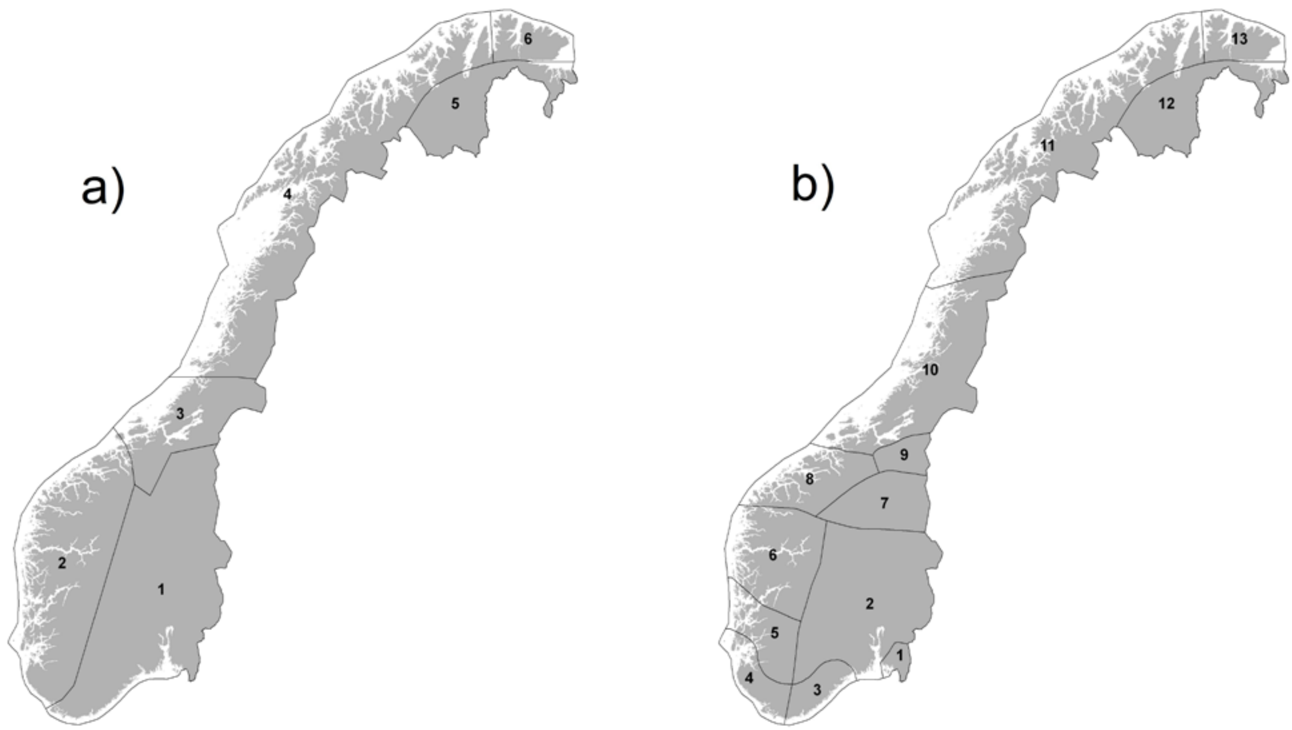


Figure 3.3 Temperature regions (a) and precipitation regions (b).

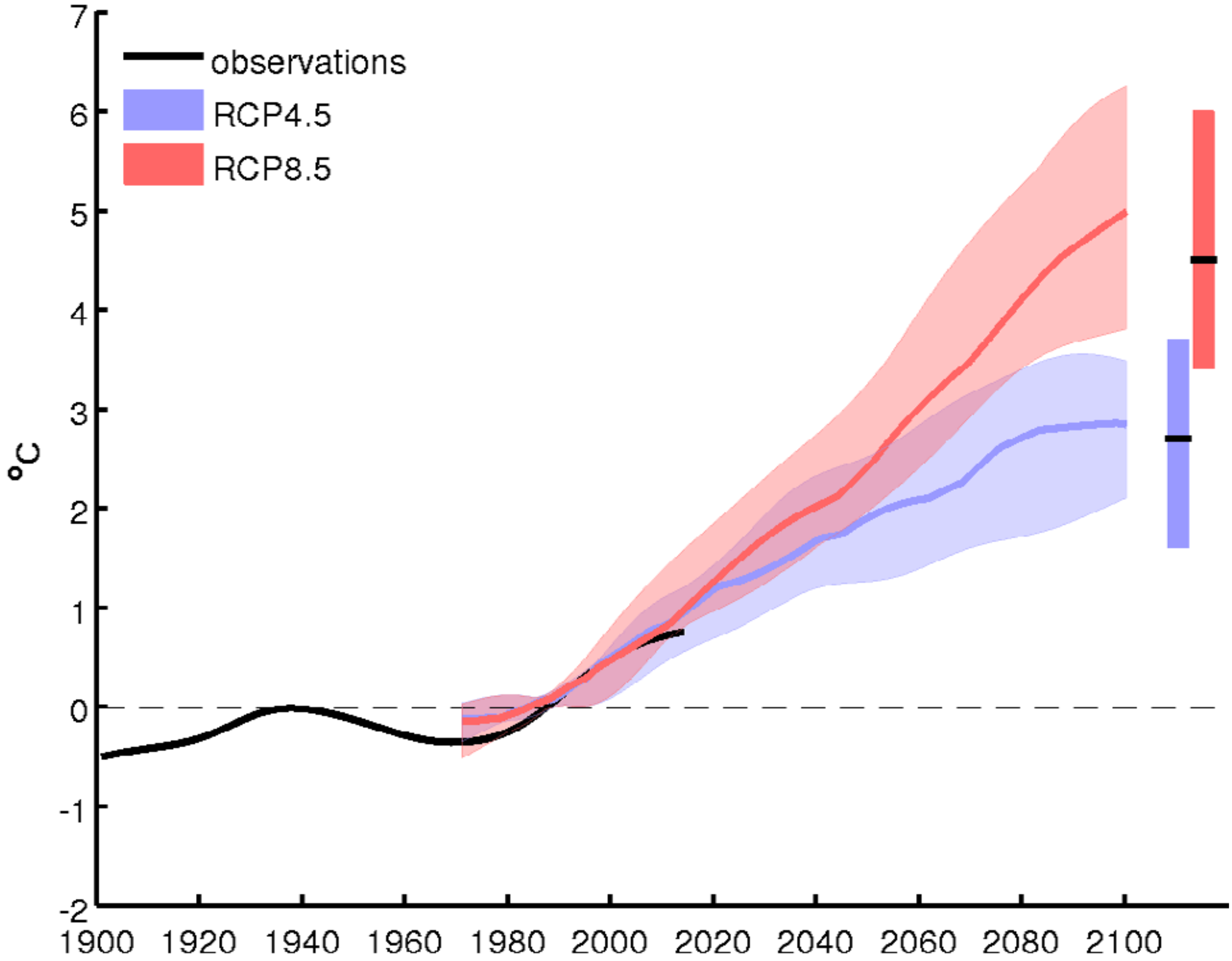


Figure 3.4 Annual temperature for Norway as deviation (in °C) from the mean for the reference period 1971-2000. Black curve shows observations (1900-2014), red and blue curve show median value for the ensemble of ten RCM simulations for emission scenarios RCP4.5 and RCP8.5. All curves are smoothed by low-pass filtering. Shading indicates spread between low and high climate simulation (10th and 90th-percentile). The box plots on the right show values for 2071-2100 for both scenarios.

Temperature region:	1	2	3	4	5	6	Norway
RCP2.6, ESD	1,4	1,2	1,4	1,6	2,3	2,1	1,6
RCP4.5, RCM	2,5	2,3	2,6	3,0	3,6	3,7	2,7
RCP4.5, ESD	2,3	2,3	2,4	3,1	4,5	3,9	2,7
RCP8.5, RCM	4,2	3,9	4,2	5,0	6,0	6,1	4,5
RCP8.5, ESD	4,4	3,5	3,8	4,4	6,7	6,2	4,6

Table 3.2 Median projections of changes in annual mean temperature (°C) from 1971-2000 to 2071-2100 for different regions (1-6, see Figure 3.3a) and for the Norwegian mainland.

The medians of the dynamically downscaled projections (Ch. 2.2), indicate that annual temperature for Norway will increase by 2.7 °C for emission scenario RCP4.5, and by 4.5 °C for RCP8.5 until the end of the century (Figure 3.4). The bulk of the simulations (10 and 90 percentiles) show an increase between 1.6 °C to 3.7 °C for RCP4.5, and 3.4 °C to 6.0 °C for RCP8.5 (Figure 3.4). For the projections based on empirical-statistical downscaling (Figure 3.5, bottom right) the annual median values are very similar to the values projected by dynamic downscaling, but the model spread is somewhat larger. For the low emission scenario, RCP2.6, the annual median value indicates a warming of 1.6 °C, with the bulk of the simulations between 0.9 °C to 3.1 °C. Accordingly, the warming for RCP2.6 until the end of the century is only slightly lower than the projected values for RCP4.5 towards mid-century (Figure 3.5).

Projections of temperature changes have also been made for the temperature regions shown in Figure 3.3a. The greatest changes in annual mean temperature are estimated for the northern parts of Norway (Table 3.2; Figure 3.5), where the median warming is ~2 °C for RCP2.6, ~4 °C for RCP4.5, and ~6 °C for RCP8.5 by the end of the century. For Western Norway the estimated warming is considerably lower; for RCP8.5 the median value is there close to the global average estimate of +3,7 °C in 100 years. For all regions the results of the two downscaling methods are largely in line both for the middle and end of the century, although there - as for the national average - is a tendency to larger span between high and low projections for the statistical downscaling. This may be due to that the ensemble of the ten projections used in the dynamical downscaling does not represent the entire span of the global models. On the other hand, the agreement between median values, projected by using both methods, indicates that the annual median RCM-values are representative for the total span of IPCC (2013) global model simulations.

For all seasons, the projections indicate a warming in Norway (Figure 3.6). This also applies to each of the six temperature regions. A general trend is that the projected warming is greater for winter (DJF) than for summer (JJA). This is more pronounced inland than along the coast; more pronounced in the north than in the south, and more pronounced for RCP8.5 than RCP4.5. Generally, the statistical downscaling indicates greater warming in winter and less warming in summer than the dynamical downscaling. These differences must be seen as part of the uncertainty in the estimates.

In the following calculations of derived values of temperature, only the median value (50th percentile) from dynamic downscaling are applied. This is because these derived indicators require daily values, which have not yet been calculated using statistical downscaling.

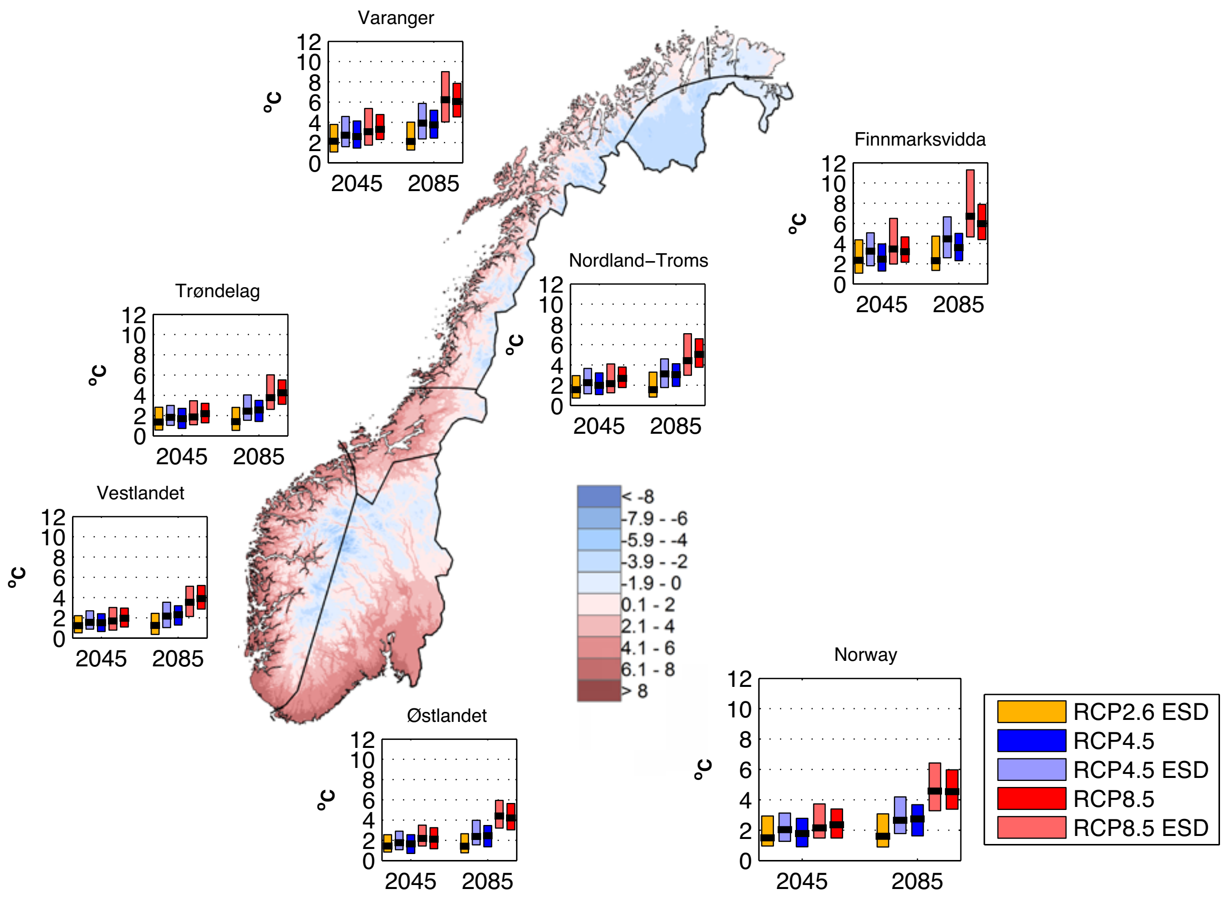


Figure 3.5 Projected change in annual temperature (°C) from the period 1971-2000 to 2031-2060 ("2045") and 2071-2100 ("2085") for emission scenarios RCP2.6 (yellow), RCP4.5 (blue) and RCP8.5 (red) for different regions. ESD simulations are made for all scenarios; RCM simulations for RCP4.5 and RCP8.5. Median projections are indicated with a bold black line, while low and high projections are respectively lower and upper part of the boxes. The figure includes graphs for six temperature regions, and for the Norwegian mainland ("Norway", bottom right). The background map shows annual temperature (°C) in the reference period 1971-2000, and boundaries between the different temperature regions are marked with black lines.

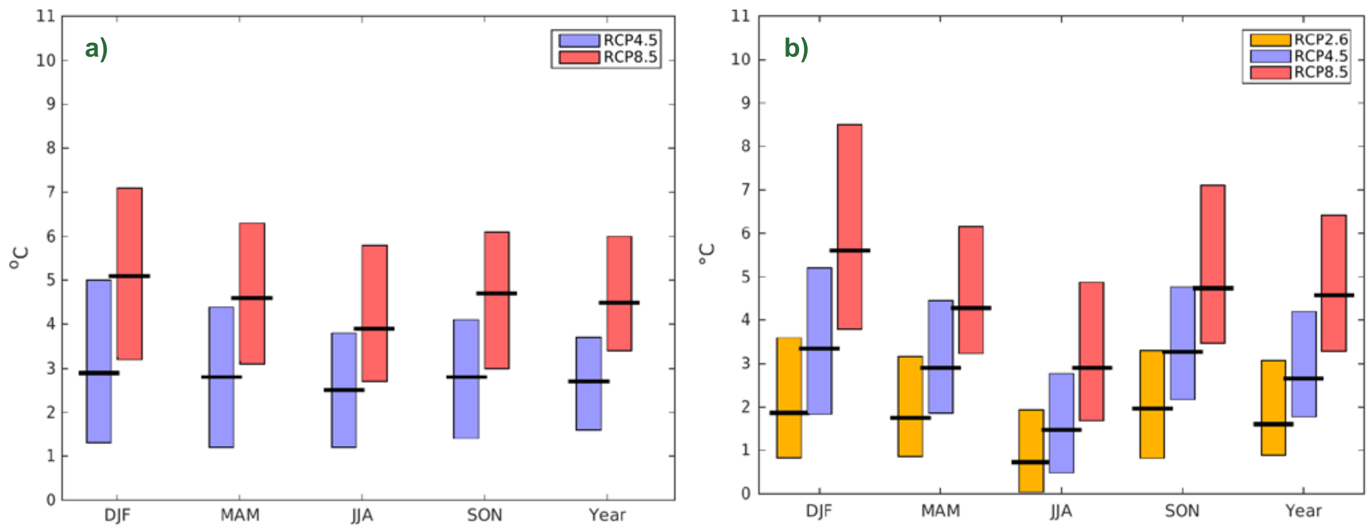


Figure 3.6 Estimated changes in seasonal and annual temperature (°C) for Norway based on downscaling by RCM (a) and ESD (b). The figures show changes from 1971-2000 to 2071-2100 for emission scenarios RCP2.6 (yellow), RCP4.5 (blue) and RCP8.5 (red). The median projection is indicated as bold black line, while low and high projections are respectively lower and upper part of the boxes.

3.1.3 Warm days

"Warm days" are in this report defined as days when the daily mean temperature exceeds 20 °C. In the reference period 1971-2000 there are rather few "warm days" per year. The highest annual average numbers lie mainly within the interval of 4-10 days/year, and are mainly recorded in South-eastern Norway (Figure 3.7a). A study of trends in maximum and minimum temperatures during the latest 60 years, demonstrated a general tendency of a larger increase in minimum temperature compared to mean temperature (Førland et al., 2016). These results are consistent with global trends (IPCC, 2013). The increase in minimum temperatures has significantly contributed to the increase in daily mean temperature and thus to the increase of number of days with temperatures above certain limits.

The number of "warm days" is estimated to increase, especially in south-eastern parts of the country (Figure 3.7b,c). For RCP8.5 some south-eastern areas will have about 30 warm days a year around year 2100 compared to the present level of around 10 days. For RCP8.5, even some inland regions from Northern Trøndelag to Finnmark will experience in average five or more warm days per year by the end of the century.

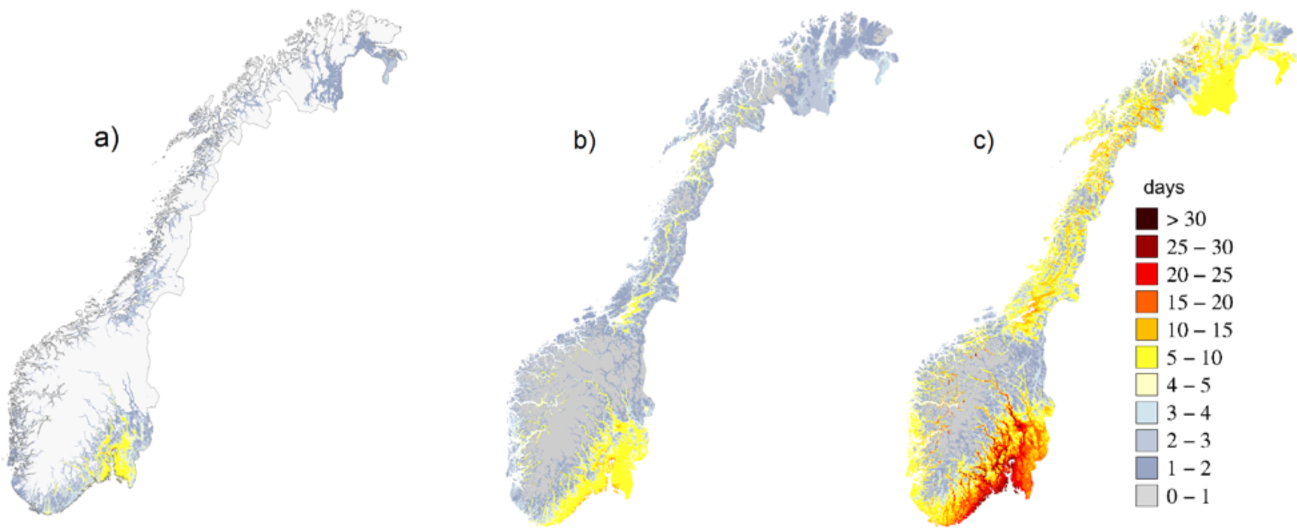


Figure 3.7 Number of days with daily mean temperature above 20 °C in a) 1971-2000, and according to median projections for b) RCP4.5 and c) RCP8.5 by the end of the century (2071-2100).

3.1.4 Growing season and heating season

In this report, the number of days with mean temperature above 5°C is used as an indicator of the length of the growing season. In the reference period the longest growing season (210-240 days, see Figure 3.8a) is found along the coast of Western Norway, and the shortest (<60 days) in the mountains. A total area of ~37,000 km^2 has a growing season lasting more than six months.

Towards year 2100, the thermal growing season will become longer, especially along the coast. For emission scenario RCP4.5, an increase of one to two months is projected for large parts of the country; with smaller changes in inland areas, and more than two months increase in northwestern and northern coastal areas (Figure 3.8 b). For RCP8.5 (Figure 3.8c), the projected increase in growing season is roughly one month higher than for RCP4.5. The area with a growing season longer than six months, is projected to increase from about 37,000 km^2 in the reference period to 105,000 (RCP4.5) and 165,000 km^2 (RCP8.5) by the end of the century.

During the reference period 1971-2000, the "heating season" for buildings (Førland et al., 2004) was slightly shorter than eight months in outer coastal areas in southern and western regions, while in the mountains and in large parts of northern Norway the heating season lasted more than 11 months. The "heating degree days-indicator (HDD)" (Førland et al., 2004) was around 3000 in the southern coastal areas, and higher than 7000 in mountain areas and parts of Northern Norway. Until year 2100, the heating season will become shorter, and for RCP4.5 the projected reduction in HDD ranges from 600 in parts of Southern Norway up to 1800 in parts of Northern Norway. For RCP8.5, the projected reduction in HDD is 500 to 600 higher than for RCP4.5.

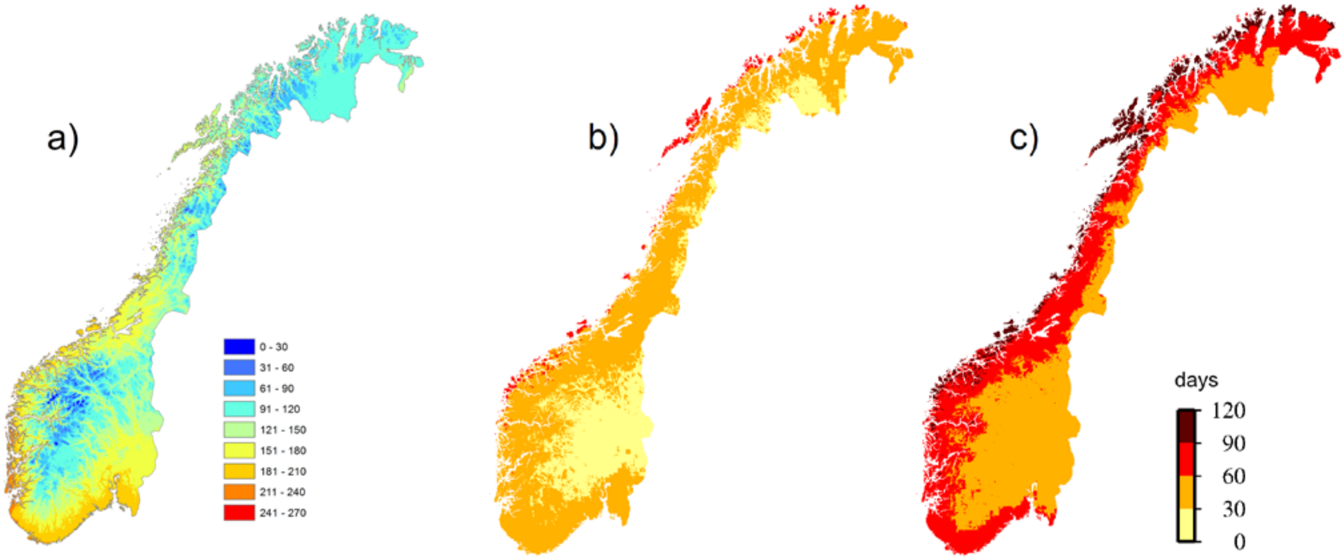


Figure 3.8 Length of growing season (days) in the reference period 1971-2000 (a), and increase (days) in length of growing season from 1971-2000 to 2071-2100 for b) RCP4.5 and c) RCP8.5.

3.2 Precipitation

3.2.1 Annual and seasonal precipitation

For the pre-instrumental age, reconstructions indicate a rapid increase in annual precipitation just after the end of the Ice Age, with maximum values in the same period when the summer temperature was at its peak, i.e. 8000 to 6000 years ago.

For the reference period (1971-2000), the mean annual precipitation for the Norwegian mainland is estimated to be 1600 mm. Annual precipitation is highest (>3500 mm) in central parts in western Norway and lowest (~300 mm) in the upper part of the valley Gudbrandsdalen (south-eastern Norway) and in interior parts of Finnmark county. Annual precipitation over Norway has increased since 1900 (Figure 3.9), and particularly from the late 1970s. For the country as a whole the increase in annual precipitation is approximately 18 % (table 3.3).

For different regions in Norway (Figure 3.3b), the relative increase is largest in precipitation region 1 (Table 3.3), but there are statistically significant positive precipitation trends in all regions except for regions 3 and 13. Seasonally, for the Norwegian mainland as a whole, the relative increase was greatest in spring (+27 % since 1900), and smallest (12 %) in summer.

Until the end of the century, the median projection indicates an increase in annual precipitation for Norway of 8 % (emission scenario RCP4.5) and 18 % (RCP8.5), see Table 3.4. Figure 3.10 shows that most (80 %) simulations indicate an increase between 3 to 14 % (RCP4.5) and 7 to 23 % (RCP8.5). The median projection for RCP8.5 gives changes comparable with the long-term trend through the last century (Table 3.3), while the RCP4.5 projection indicates that rainfall will increase considerably slower in the future than has historically been observed. The largest relative change in annual precipitation is estimated for the northern regions of Norway (Table 3.3). In absolute numbers (millimeters), the largest changes are found in western parts of Norway.

The precipitation projections indicate an increase for all seasons (Figure 3.11). The spread among the different models is considerable, and there is no consistency between models and scenarios in terms of what season the relative changes are seen to be greatest. For example, the median projection for emission scenario RCP8.5 indicates that the relative change at the end of the century is greatest winter and fall, while for RCP4.5 the greatest increase is found for spring and summer (Figure 3.11). The regional projections (not shown) indicate largest relative increase east of the watershed in winter and in central and northern Norway in summer.

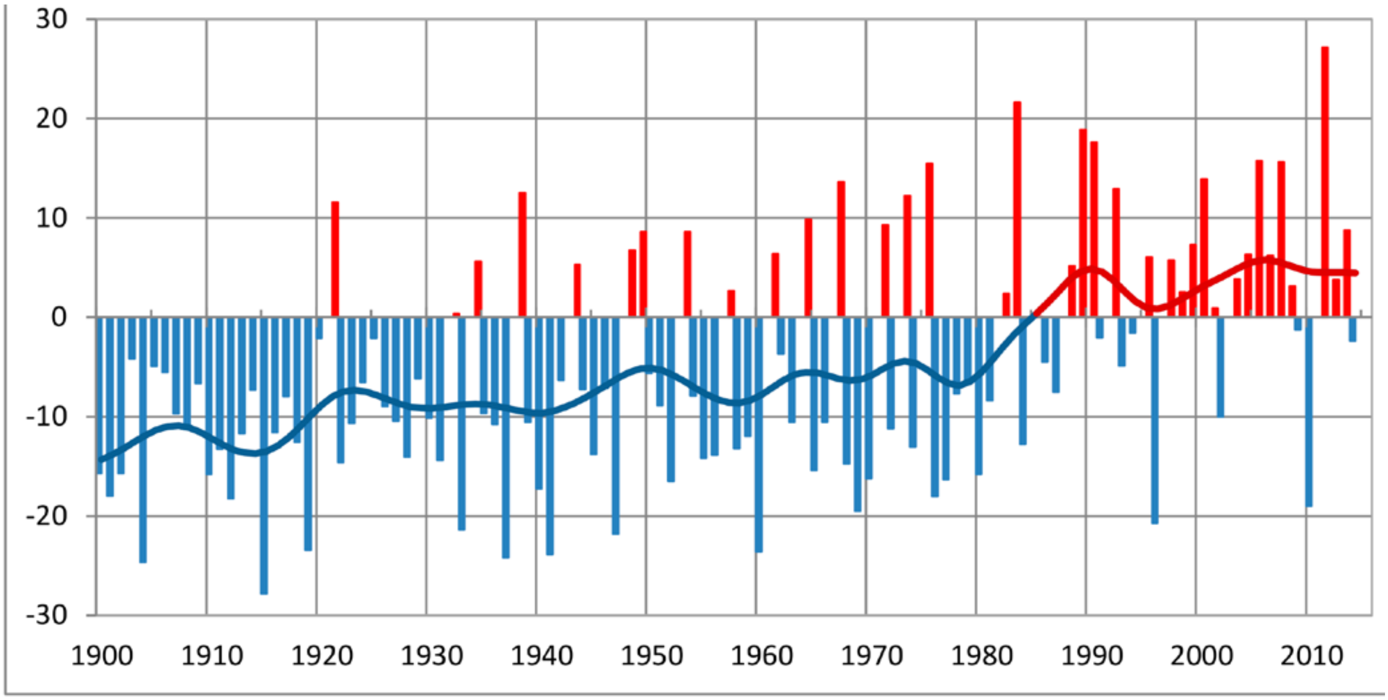


Figure 3.9 Annual precipitation for the Norwegian mainland 1900–2014. The figure shows deviations (%) from the mean annual precipitation during the period 1971–2000.

Region:	1	2	3	4	5	6	7	8	9	10	11	12	13	N
Annual	**2,3**	**1,5**	1,0	**2,0**	**1,9**	**1,8**	**1,8**	**1,5**	**1,3**	**1,7**	**1,6**	**1,7**	0,2	**1,6**
Winter	2,5	1,4	1,2	2,0	1,8	1,4	1,3	1,7	1,8	1,9	1,7	**2,1**	-1,7	1,6
Spring	1,7	1,5	0,1	1,5	2,2	**2,6**	**2,7**	2,3	**2,1**	**3,1**	2,3	**2,4**	0,3	**2,3**
Summer	1,6	0,9	0,4	1,0	0,4	0,9	1,4	1,1	0,8	0,7	1,8	**1,8**	2,2	1,0
Autumn	**3,0**	2,2	1,8	**2,8**	**2,5**	**2,1**	**2,0**	1,1	1,0	1,3	1,1	0,9	0,0	**1,7**

Table 3.3 Linear trends (percent per decade) in annual and seasonal precipitation during 1900-2014. Trends are presented for different regions 1-13 (see Figure 3.3b) and for the Norwegian mainland as a whole (N). Trends are expressed as percentage of precipitation during the reference period 1971-2000. Bold numbers indicate trends statistical significant at the 1 %-level (Mann-Kendall non-parametric test).

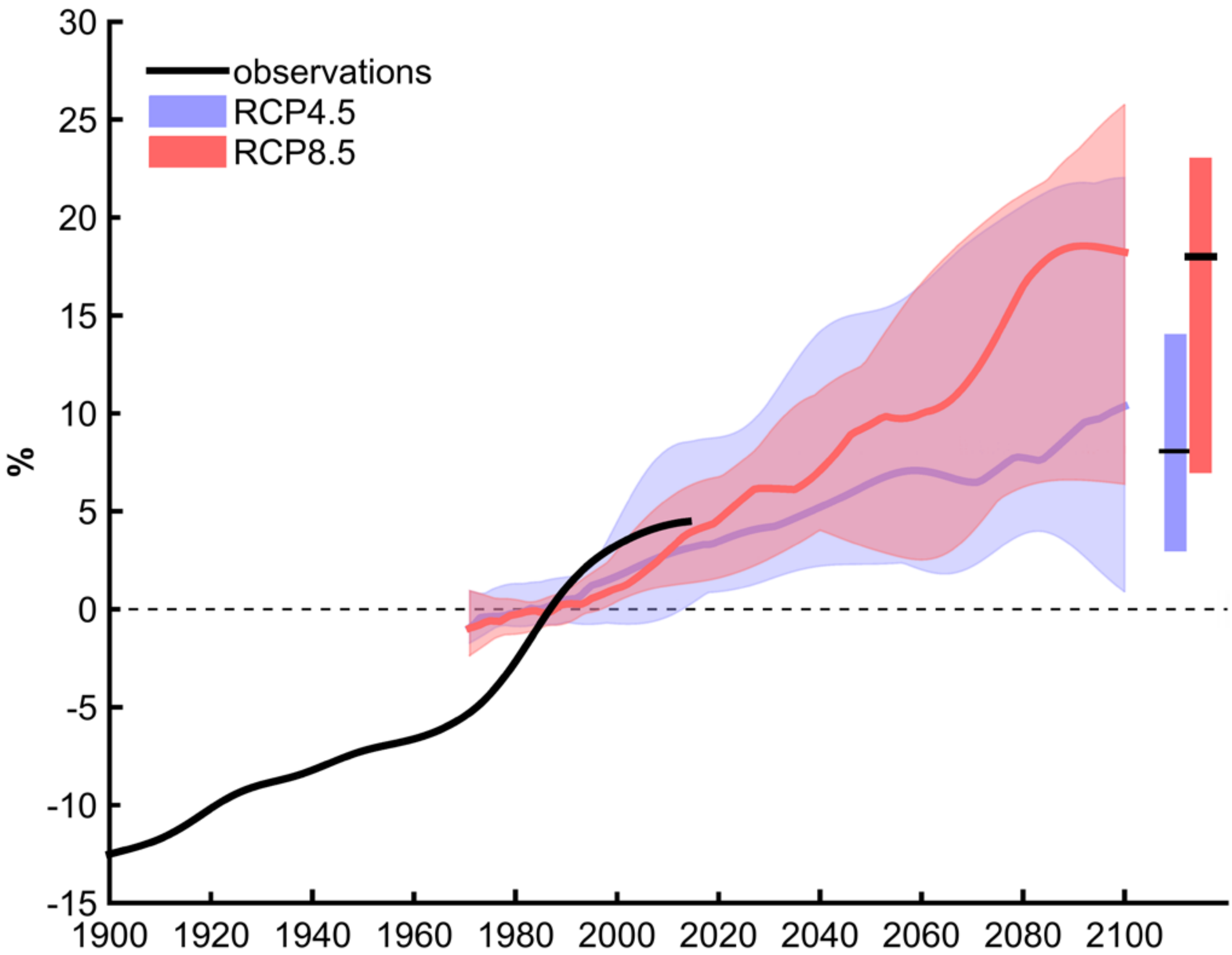


Figure 3.10 Annual precipitation over Norway as deviation (%) from the period 1971-2000. Black curve represents observations (1900-2014), red and blue curved lines show median values for the ensemble of ten RCM simulations for emission scenarios RCP8.5 and RCP4.5. All curves are smoothed. Shading indicates the spread between low and high climate simulation (10th and 90th-percentile). The box plot on the right shows projections up to 2071-2100 for both scenarios.

Region:	1	2	3	4	5	6	7	8	9	10	11	12	13	N
RCP4.5	6	8	5	6	6	8	13	6	11	11	11	13	11	8
RCP8.5	11	15	10	11	12	17	22	14	21	21	17	22	17	18

Table 3.4 Median projections of changes (%) in annual precipitation from 1971-2000 to 2071-2100 for different regions (1-13, see Figure 3.3b) and for the Norwegian mainland (N).

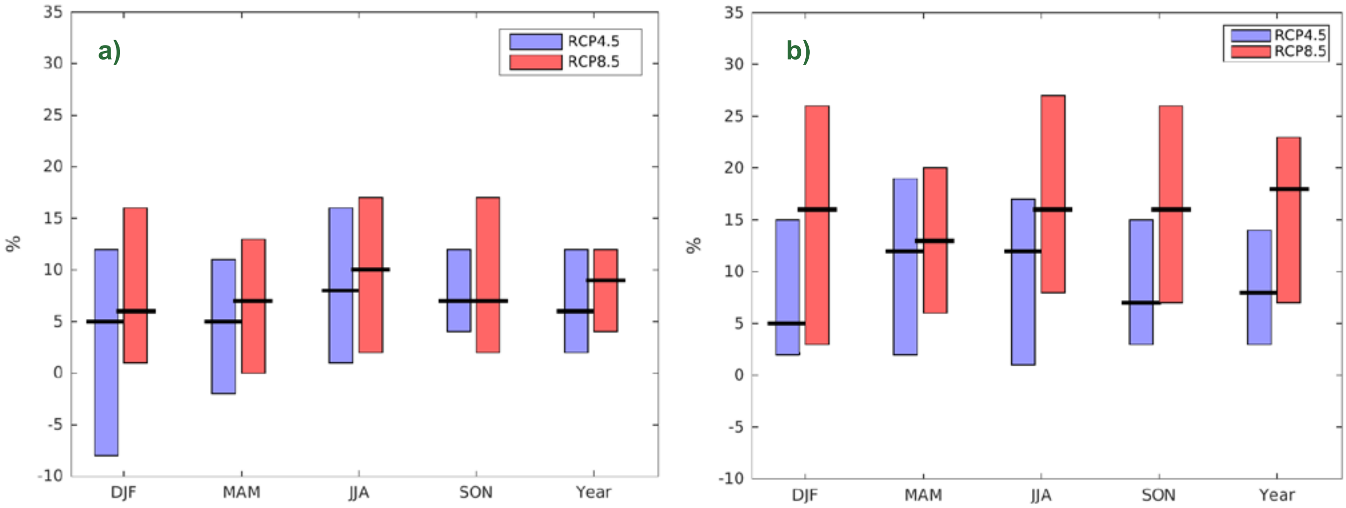


Figure 3.11 Relative changes (%) in seasonal and annual precipitation for Norway from 1971-2000 to a) 2031-2060 and b) 2071-2100 for emission scenarios RCP4.5 (blue) and RCP8.5 (red). Median projections are marked as black bar, while low and high projections are lower and upper part of the boxes.

3.2.2 Heavy rainfall

In this report, heavy 1-day rainfall is defined as the 99.5th percentile for daily precipitation during 1971 to 2000, i.e. the value was exceeded approximately twice per year on an annual basis and once every second year on a seasonal basis. A map of present day amounts of heavy 1-day rainfall is shown in Figure 3.13. The RCM-based median projections indicate an annual increase in number of days with heavy rainfall of 89 % for RCP8.5 and 49 % for RCP4.5 by the end of the century (Figure 3.12b). The largest increase is found for the winter season (143 % for RCP8.5). All models show an increase for all seasons (Figure 3.12a,b) and it cannot be ruled out that number of days with heavy precipitation will more than double by the end of the century in all seasons (high estimate is over 100 % for all seasons) under RCP8.5. An increase in number of days with heavy rainfall is projected for all regions and for all seasons.

In addition to an increase in number of days with heavy rainfall, the rainfall intensity will also increase for these days. For the Norwegian mainland the median annual projection shows an increase in 1-day rainfall intensity of 19 % for RCP8.5 and 12 % for RCP4.5 by the end of the century (Figure 3.13, Table 3.5). The increase is seen for all regions and for all seasons, with somewhat greater values in summer. The change averaged over the whole year is greatest in Northern Norway, while in absolute terms (change in the number of millimeters) the changes are largest in Western Norway. In winter, the relative changes are greatest in Eastern and Northern Norway, while summer changes are greatest in northern regions.

High-intensity rainfall during a few hours is causing large damages on infrastructure and buildings in Norway. While Western Norway has the highest values for daily, monthly and annual rainfall, the areas around the Oslofjord and along the south coast have generally the highest intensities of rainfall during a few hours or shorter. Both for intensity and frequency of short-term heavy rainfall an increase is documented in recent years (Førland et al., 2015). To obtain a preliminary indication of future changes in short-term rainfall, three-hourly values from six Euro-CORDEX models were analyzed. These analyses included changes in values that are exceeded in 0.5 % of cases (q99.5) as well as for return periods 5 and 200 years. Table 3.5 indicates that the one-day values for the limited selection (six) of models with available three-hourly values are in good agreement with the ten models used for heavy daily rainfall above.

When estimating future rainfall design values, a so-called "climate factor, Kf" is often applied. Kf is the factor one must multiply the current rainfall design values to get a measure for future design values (Paus et al., 2015). The climate factor depends on return period, rainfall duration, geographical location, reference period, scenario period and climate models (global/regional). Table 3.5 demonstrates higher climate factors for high emissions (RCP8.5) than for moderate emissions (RCP4.5), higher factors for three-hourly vs. one-day rainfall, and higher factors for increasing return periods; i.e. 99.5th percentile vs. 5 and 200 years return periods. These tendencies to higher climate factors for shorter durations, and higher return periods, are consistent with results from other countries (Paus et al., 2015; Westra et al., 2014). More details can be found in Førland et al. (2016).

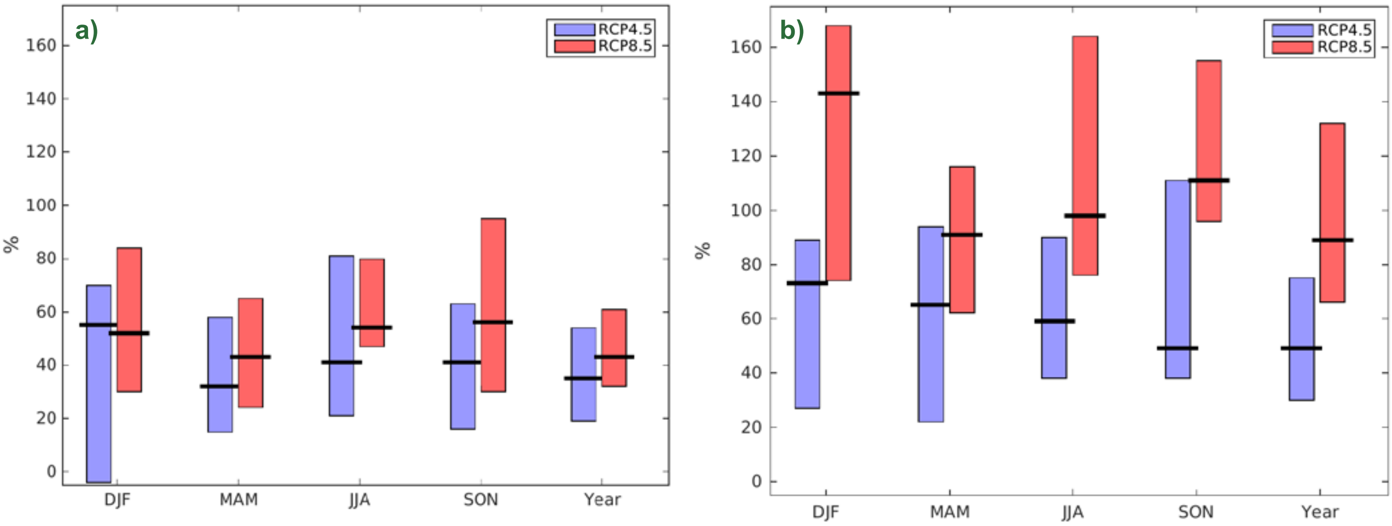


Figure 3.12 Relative changes (%) in number of days with "heavy rainfall" from 1971-2000 to a) 2031-2060 and b) 2071-2100 for emission scenarios RCP4.5 (blue) and RCP8.5 (red). Median projections are given as black bars, while low and high projections are the lower and upper part of the boxes.

Scenario:	**RCP4.5**			**RCP8.5**		
Duration:	**3 hours**	**1 day**	**1 day**	**3 hours**	**1 day**	**1 day**
Indicator ↓	**(6 models)**		**(10 models)**	**(6 models)**		**(10 models)**
q99,5	**1,11**	**1,11**	**1,12**	**1,20**	**1,20**	**1,19**
M5	**1,16**	**1,13**	**x**	**1,28**	**1,22**	**x**
M200	**1,19**	**1,14**	**x**	**1,38**	**1,26**	**x**

Table 3.5 Climate factors for 3-hour and 1-day precipitation for changes from 1976-2005 to 2071-2100 for the emission scenarios RCP4.5 and RCP8.5. Values are averaged over the Norwegian mainland, and are based on changes above the 99.5th percentile (q99.5), and values with return periods of 5 years (M5) and 200 years (M200).

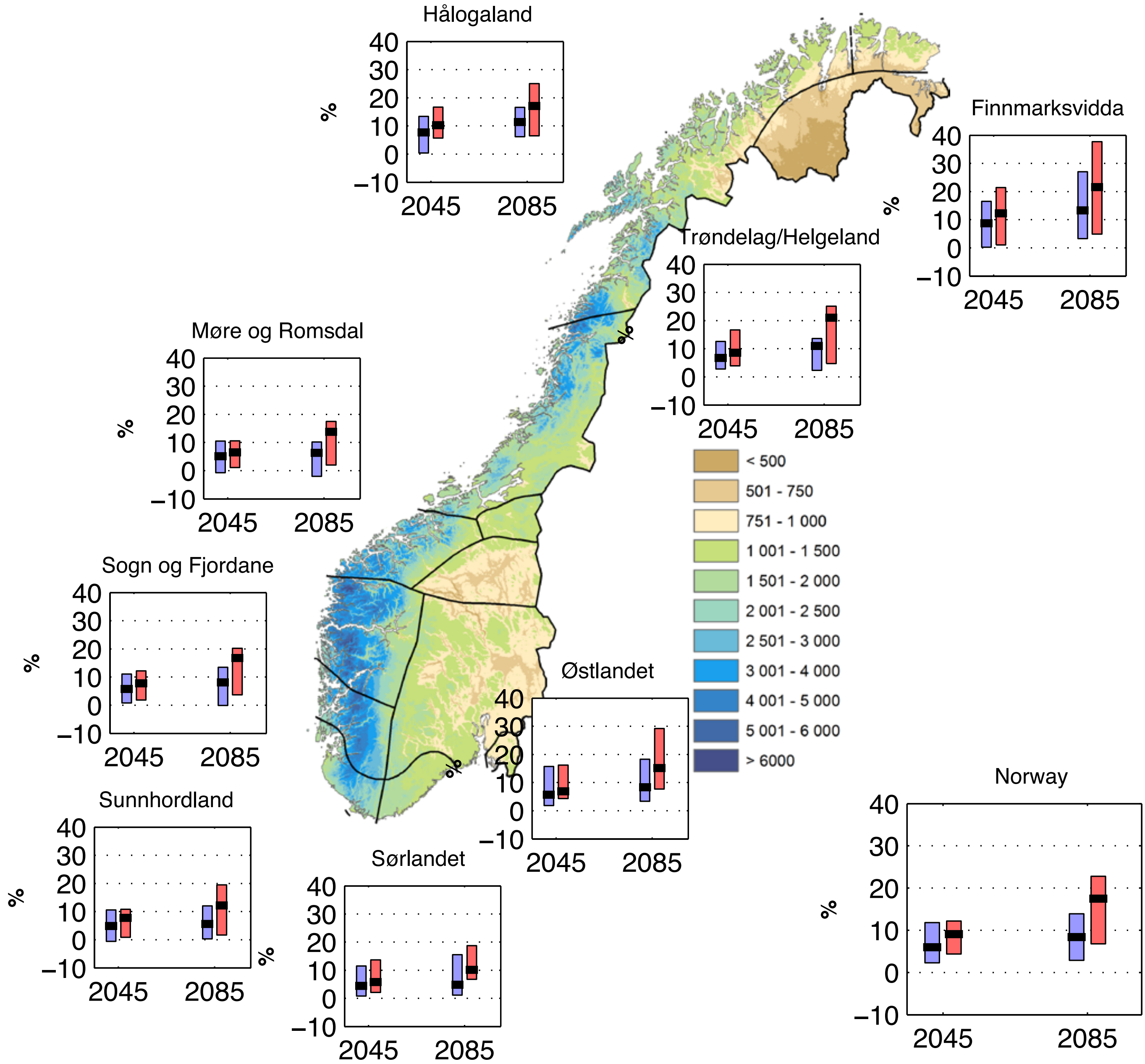


Figure 3.13 Relative changes (%) in rainfall intensity on days with heavy 1-day rainfall. The box plots show changes from 1971-2000 to 2031-2060 ("2045") and 2071-2100 ("2085") for different regions and for two emission scenarios RCP4.5 (blue) and RCP8.5 (Red). Median projection is marked in black, while low and high projections are respectively lower and upper end of the boxes. The figure includes graphs from selected regions, and for the Norwegian mainland ("Norway", bottom right). The background map shows amount (mm) of 1-day heavy rainfall (99.5th percentile) during the period 1971-2000.

3.3 Wind

Along the coast and in the mountains the 99th percentile for wind speed is gale or more, i.e. winds speed above 15 m/s (Figure 3.14a). During the period 1961-2010, most of the country has experienced a slight increase in wind velocities above this threshold (Figure 3.14b), but there are large variations from year to year and between different localities.

The Euro-CORDEX projections for future wind indicate small changes in median value of wind speed exceeded in 1 % of the time. For absolute maxima values there are increases for all seasons of up to 20 % for some models. However, the main conclusion is that the projections indicate small changes in average as well as for high wind speeds. More details on the wind analyses can be found in Førland et al. (2016).

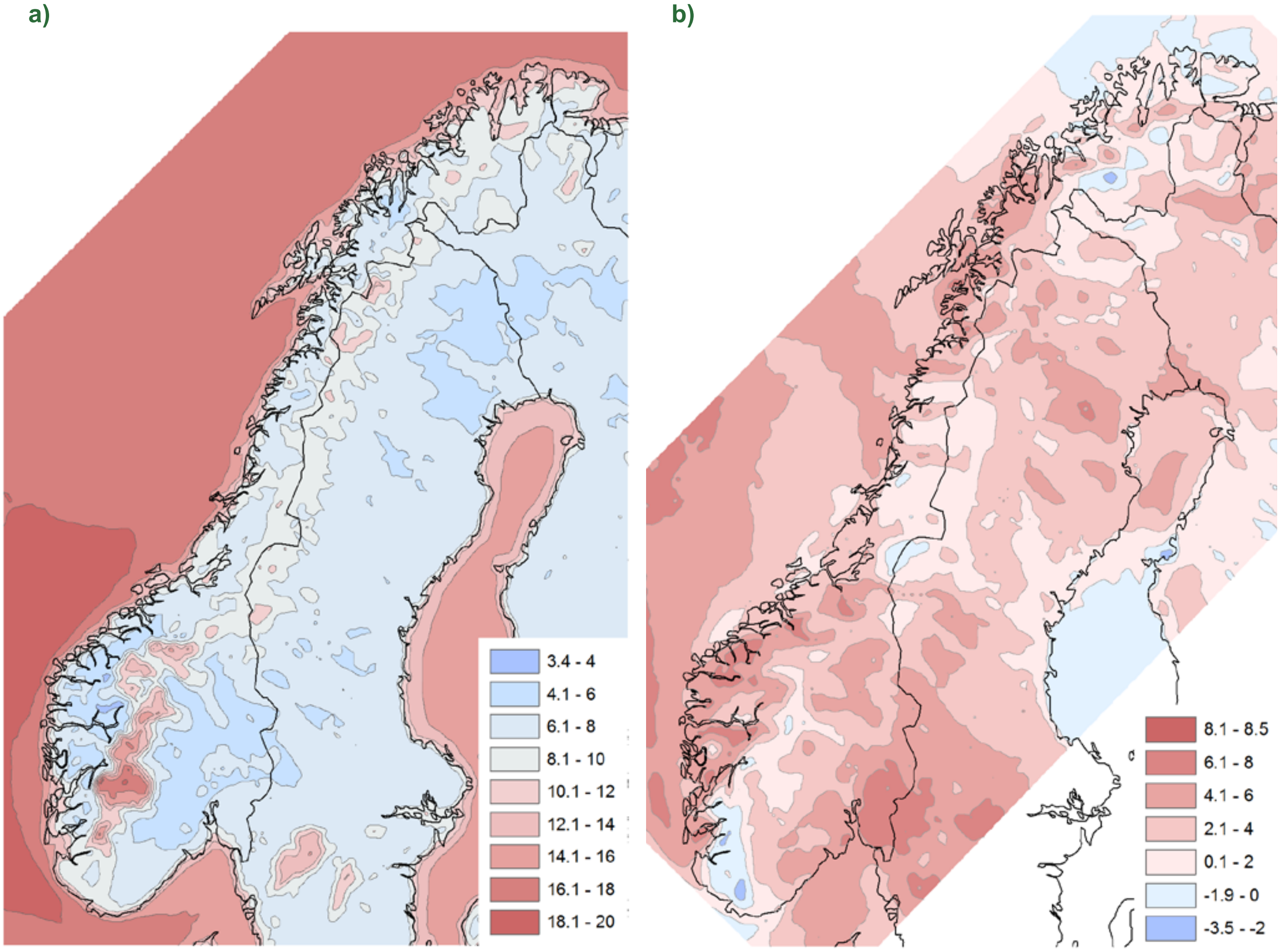


Figure 3.14 Model estimates of 99th percentile for wind speed based on the NORA10-dataset (Reistad et al., 2011). a) Annual values (m/s) for the period 1971-2000. b) Linear trends (%) from 1961 until 2010.

4. Hydrology

The hydrological cycle describes how water precipitates over land, how it accumulates in the form of snow and ice or infiltrates into the ground as soil moisture and is stored as groundwater, how it evaporates into the atmosphere or runs off in rivers until it reaches the oceans. Water evaporates from the ocean as well as the land surface, giving atmospheric moisture for subsequent precipitation. Climate change will both intensify and weaken different components and processes in this cycle.

4.1 Annual and seasonal runoff

Runoff and evapotranspiration have been estimated using a gridded 1 x 1 km^2 hydrological model covering the whole of Norway. For the reference period (1971-2000), the mean annual runoff in Norway is approximately 1100 mm and evapotranspiration is approximately 500 mm. The uncertainty in these estimates is up to 25 %. Annual runoff varies considerably from more than 5000 mm at the glacier Ålfotbreen in western Norway to less than 400 mm in the upper part of the valley Gudbrandsdalen and in interior parts of Finnmark. The increase observed for precipitation since 1900, is not to the same extent reflected in runoff (Figure 4.1). A likely explanation is that the observed increase in temperature has increased evapotranspiration.

The changes in seasonal runoff are more pronounced than for annual runoff. Comparing the percentage change for annual and seasonal runoff between 1971-2000 and 1985-2014 for the whole of Norway and for different regions in Norway, an increase in winter and spring runoff is evident (Figure 4.2). This tendency is confirmed in a trend study of long records (1920-2005) of river flow (Wilson et al., 2010). An explanation for this is that the increased temperature results in more precipitation, and a larger proportion falling as rain rather than snow in the winter and spring seasons. Increased temperatures also lead to an earlier snowmelt.

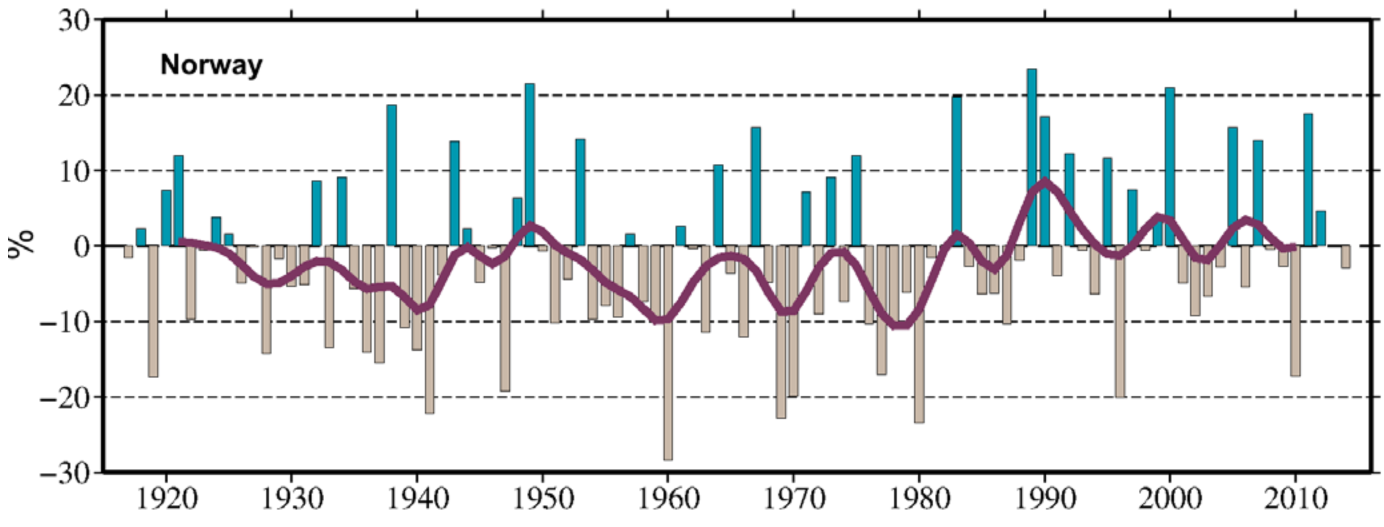


Figure 4.1 Annual runoff (% deviation from 1971-2000 mean) for the Norwegian mainland during the period 1917–2014. The solid line shows 10-year Gauss-filtered values.

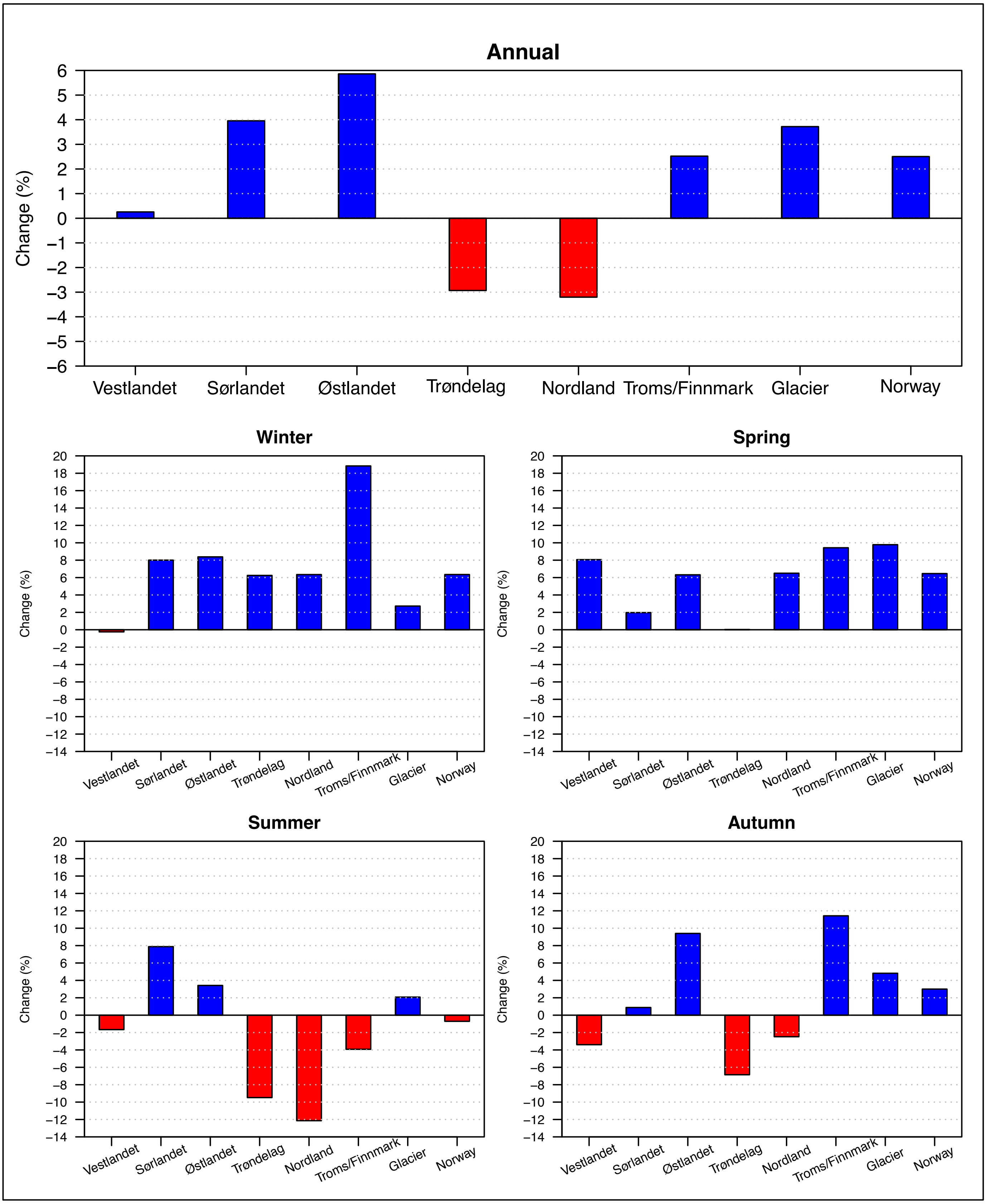


Figure 4.2 Change (%) in annual and seasonal runoff from 1971-2000 to 1985-2014 for the whole of Norway, for six regions and for a group comprised of river basins with glaciers.

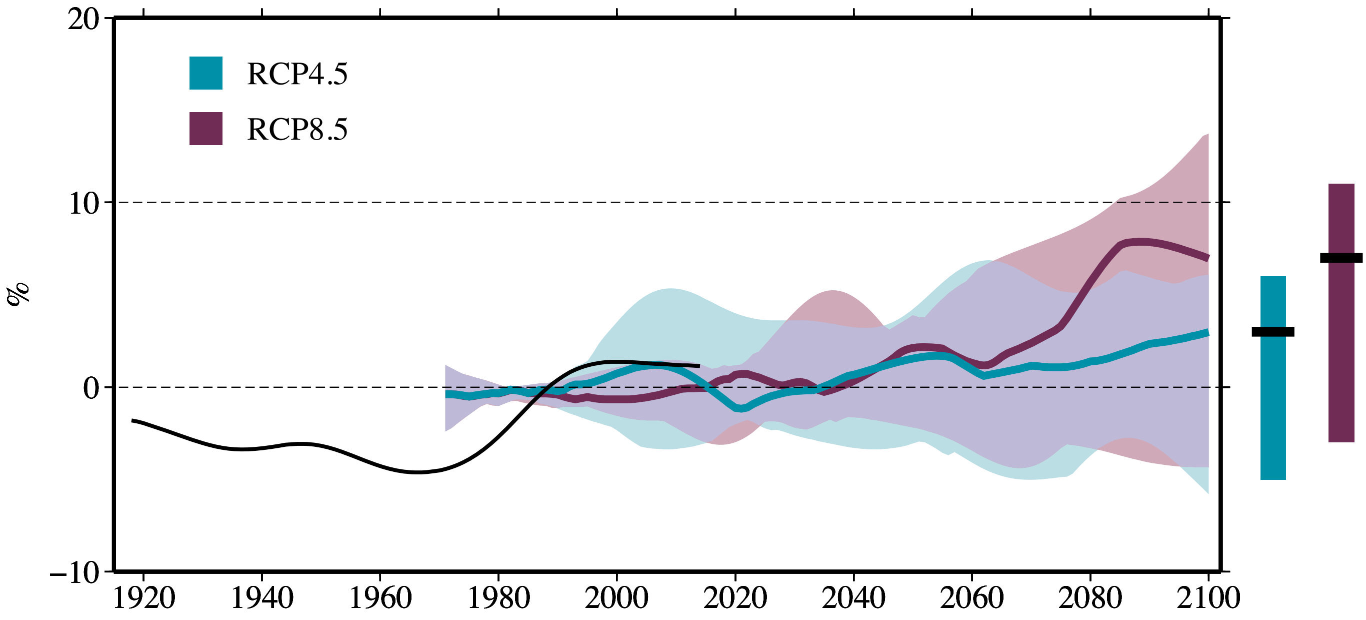


Figure 4.3 Annual runoff over Norway as a deviation (%) from the period 1971-2000. The black line represents observations (1917-2014), and red and blue lines show median values for the ensemble of ten RCM simulations for emission scenarios RCP8.5 and RCP4.5. All curves are smoothed to remove short-term variability. Shading indicates the spread between the various climate simulations (shown as the 10 and 90-percentiles). The box plots on the right show projections up to 2071-2100 for both scenarios.

Up to the end of the century, the median projection indicates a slight increase in annual runoff for Norway, 3 % for RCP4.5 and 7% RCP8.5 (Figure 4.3). The spread in model results is rather large.

The projected changes in seasonal runoff are considerable larger than for annual runoff (Figure 4.4). This is caused by the combined effect of changes in temperature and precipitation. The largest relative changes are expected in the winter (large increase due to increased precipitation and more precipitation that falls as rain) and in the summer (large decrease caused by earlier snowmelt and higher evaporation losses). Both emission scenarios, RCP4.5 and RCP8.5 show the same patterns, although they are more pronounced for RCP8.5. Increases in runoff are also found in the spring and autumn seasons for Norway as a whole. For the spring season, a large increase is expected at high altitudes because snowmelt will shift from early summer in the present-day climate to spring in the future. At low altitudes, spring runoff is expected to decrease, as there will be no snowmelt contributing to spring runoff in a future climate.

4.2 Floods

Climate change is expected to intensify the global hydrological cycle. This may lead to an increase in the intensity and frequency of hydrological extremes, including floods. Projections, however, are uncertain and, in particular, climate change effects on floods may be complex in regions with highly heterogeneous hydrological regimes such as Norway.

Trends in the magnitude and frequency of floods have been analysed for up to 211 pristine and near-natural catchments for the periods 1962-2012, 1972-2012 and 1982-2012 (Vormoor et al., 2016). Rainfall- and snowmelt-generated events were analysed separately. Changes in the timing of snowmelt and changes in flood regimes were also analysed.

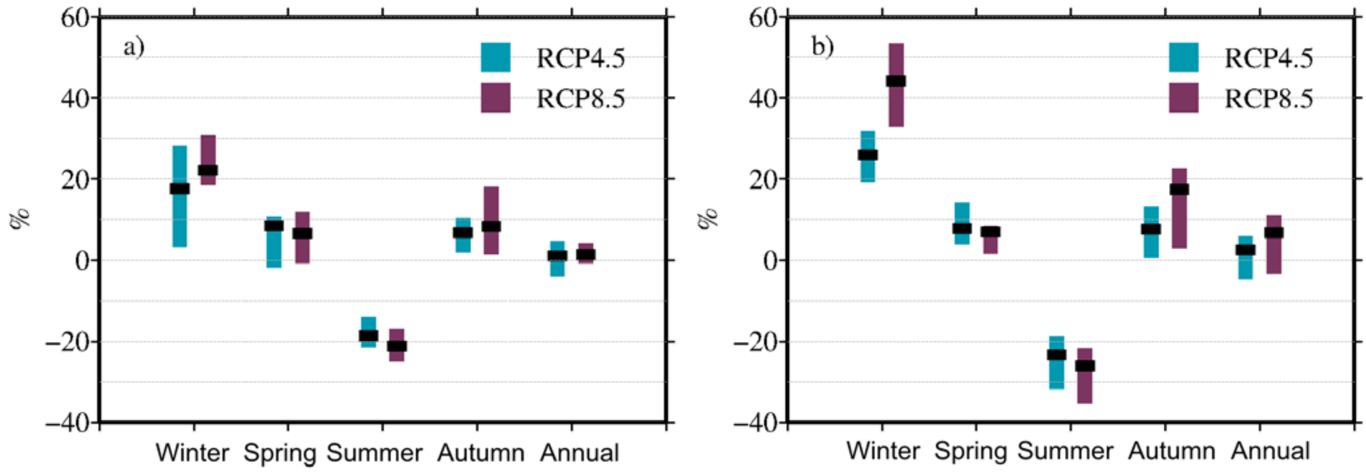


Figure 4.4 Relative changes (%) in seasonal and annual runoff for Norway from 1971-2000 to a) 2031-2060 and b) 2071-2100 for emission scenarios RCP4.5 (blue) and RCP8.5 (red). Median projections are marked as a black solid line, while low and high projections are marked by the lower and upper ends of the boxes.

The results show that:

- there are no clear changes in peak discharge over the periods considered,
- rainfall-generated floods occur more frequently, whereas snowmelt-generated floods are less common
- snowmelt occurs earlier
- the importance of rainfall for Norwegian flood regimes is increasing, while the importance of snowmelt is decreasing.

Future changes in flood magnitudes (the mean, 200- and 1000-year flood) have been analysed for 115 catchments using RCM simulations, a catchment-based hydrological model and an extreme value analysis of the simulated discharge (Lawrence, 2016). Changes in the 200-year flood between a reference period, 1971-2000 and a future period, 2071-2100 are illustrated in Figure 4.5. We see large regional differences in the projected changes across Norway, with median ensemble projections ranging from -44% to +56% for the daily-averaged flood magnitude. The results show that:

- the changes observed will intensify in the future,
- the magnitude of change strongly depends on the emission scenario (Figure 4.5),
- we can also expect rain flood magnitudes to increase and snowmelt floods magnitude to decrease. In many areas, this is also associated with a change in seasonality,
- the flood generating process is of major importance for the direction of change, but local effects such as altitude and catchment area are also important,
- the ensemble spread is relatively large, but the direction of change is consistent.

Using these observed and projected changes as related to flood generating processes in different regions and catchment types in Norway, a set of recommendations for use of a climate change factor for different catchment types has been developed. Due to the large spread in the ensemble projections for individual catchments, three ‘climate factor’ categories are recommended:

- 0 % for large rivers where snowmelt is the dominating flood generating process in today’s climate. This implies that design flood estimates can be based on up-to-date river flow observations.
- 20% or 40 % increase in the design flood estimates in all rivers dominated by rain floods and in small rivers responding quickly to heavy rain events. This implies adding 20% or 40% to the estimated design flood discharge.

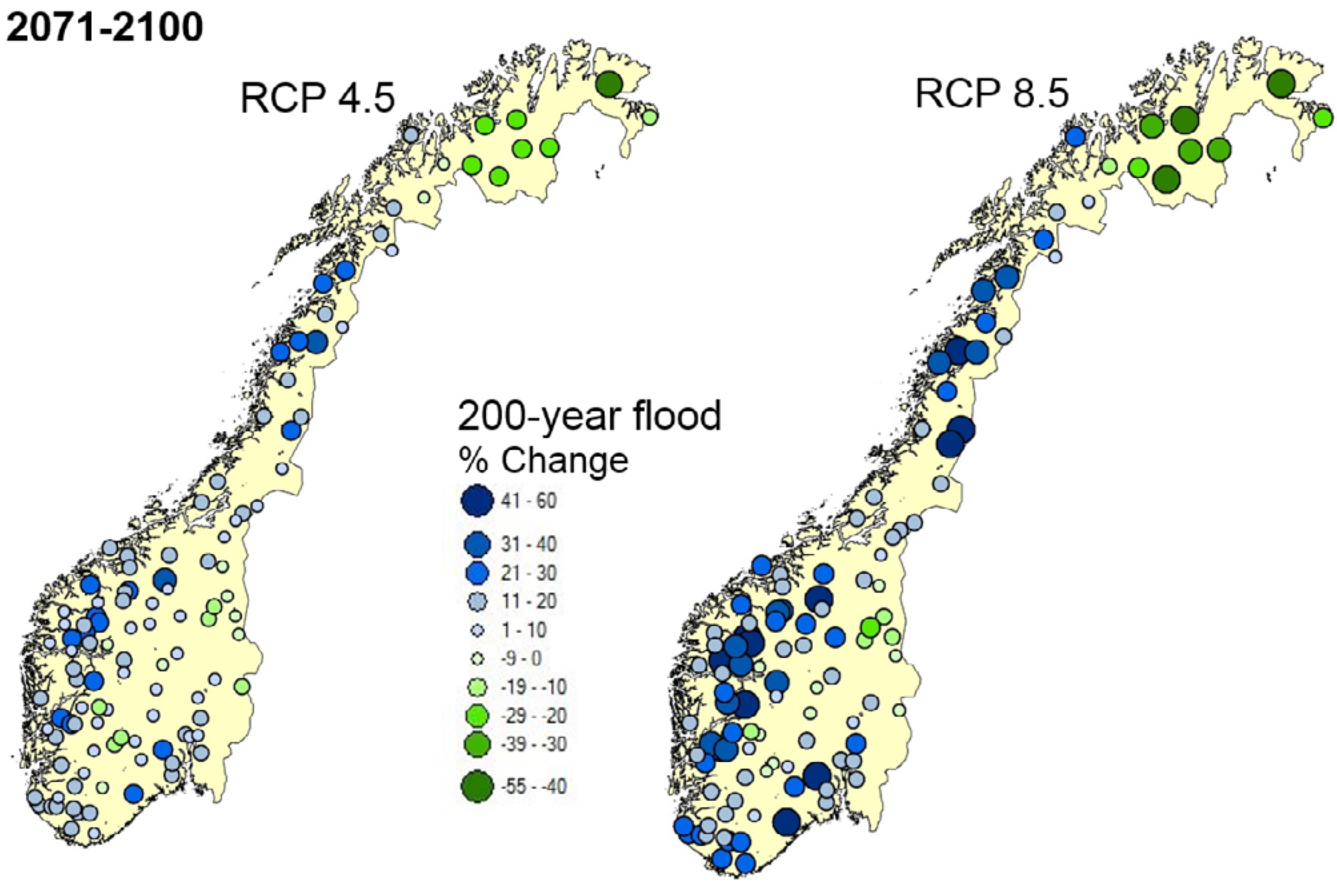


Figure 4.5 Percentage change in the 200-year flood for medium (RCP4.5) and high (RCP8.5) emissions. Green indicates a reduction and blue an increase in flood magnitude.

4.3 Droughts

Drought can be defined as a prolonged deficit of water over a larger area. It can therefore be seen as a deviation from normal precipitation, runoff, soil moisture or groundwater. A trend analysis for the period 1930-2004 indicate longer periods with low river flow in the summer in southeastern parts of Norway (Wilson et al., 2010; Stahl et al., 2010). This can be explained by increased temperature causing earlier snowmelt and higher evaporation losses.

This means that increased precipitation does not automatically mean increased soil moisture or river flow. The modelled future soil moisture indicates larger soil moisture deficits towards the end of the century, in particular under RCP8.5. Other studies (Wong et al., 2011) also show that we can expect more severe soil moisture deficits, low groundwater levels and longer low flow periods in the future. This may increase the risk of forest fires and the need for irrigation.

4.4 Snow

The combined effect of increased temperature and precipitation on snow water equivalent (SWE) is already evident in observations. In southern Norway, at elevations of 850-1350 m a.s.l., the SWE has increased since 1931 (Skaugen et al., 2012), and below this altitude the SWE has decreased. A similar pattern has been found for central and northern Norway, although it is not as clear for those regions. In general, there is a trend towards a later snow accumulation and an earlier snowmelt (Dyrrdal and Vikhamar-Schuler, 2009).

The observed changes are expected to continue in the future. Figure 4.6 illustrates changes in the expected number of days with a snow cover under a future climate. For RCP 4.5 the snow season could become one to five months shorter, and with RCP 8.5 it could become 1- 7 months shorter. At low altitudes where the winter temperature today is only slightly below zero, the snow will be negligible in most years towards the end of the century under the high emission scenario.

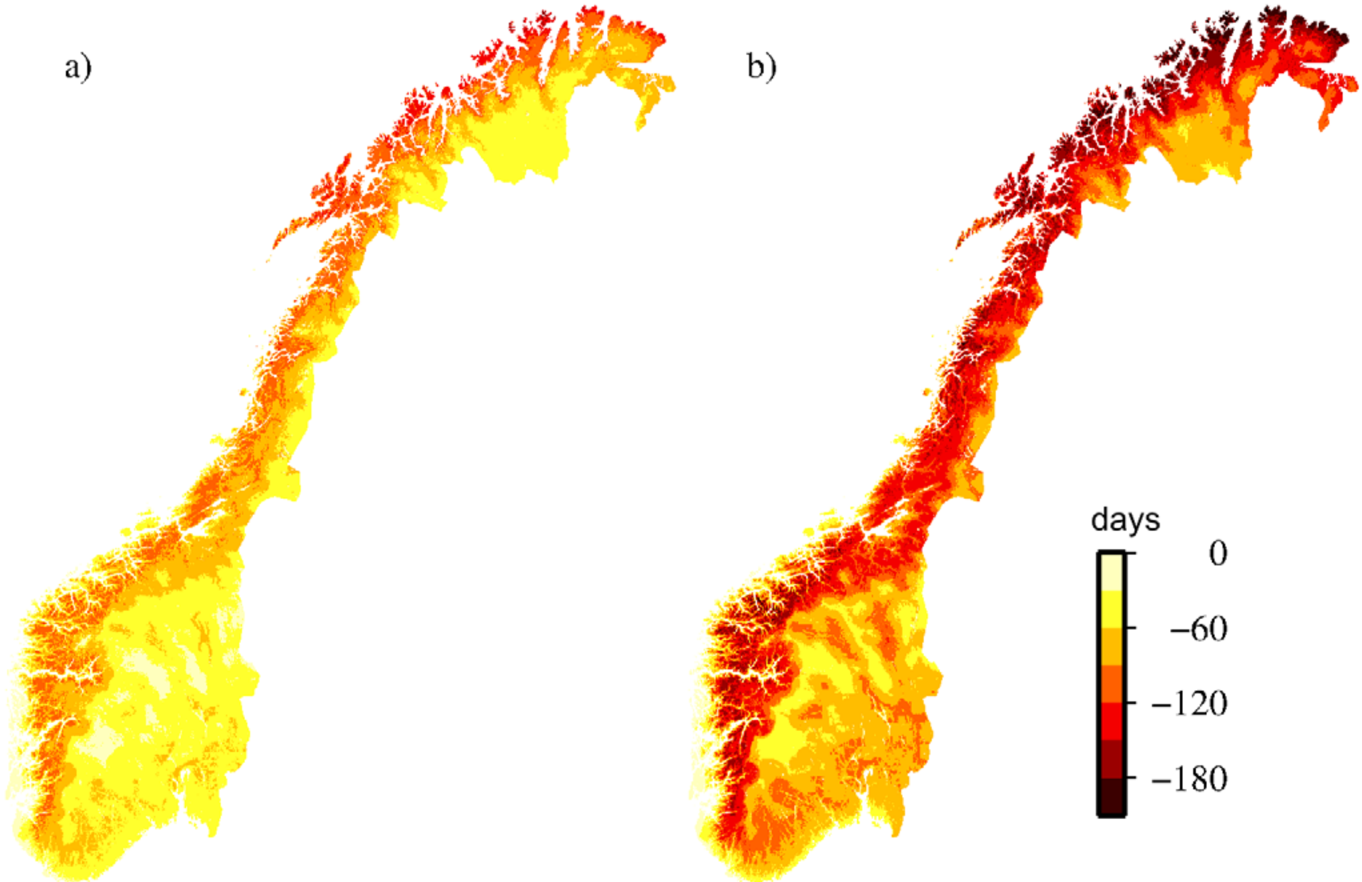


Figure 4.6 Changes in the annual number of days with snow cover from 1971-2000 to 2071-2100 for a) RCP4.5, median projection and b) RCP8.5, median projection.

4.5 Glaciers

Measurements of the positions of glacier fronts started around 1900 in Norway. They show a retreat during the 19th century, of up to 2.5 km, but there are large variations between glaciers (Figure 4.7). Inland glaciers have continuously retreated, whereas maritime glaciers have had periods of both retreat and advance. Many glaciers near the coast grew during the 1970s and the 1990s, but have had a negative mass balance since 2000.

Expected climate change under the high emission scenario will have a large impact on the area and volume of glaciers in Norway towards the end of the century. For large glaciers a reduction of up to 1/3 of the area and volume they have today is expected, such that the remaining glaciers will be significantly smaller and will only be found at higher altitudes. The largest changes in glacier area and volume are expected to occur after the middle of this century.

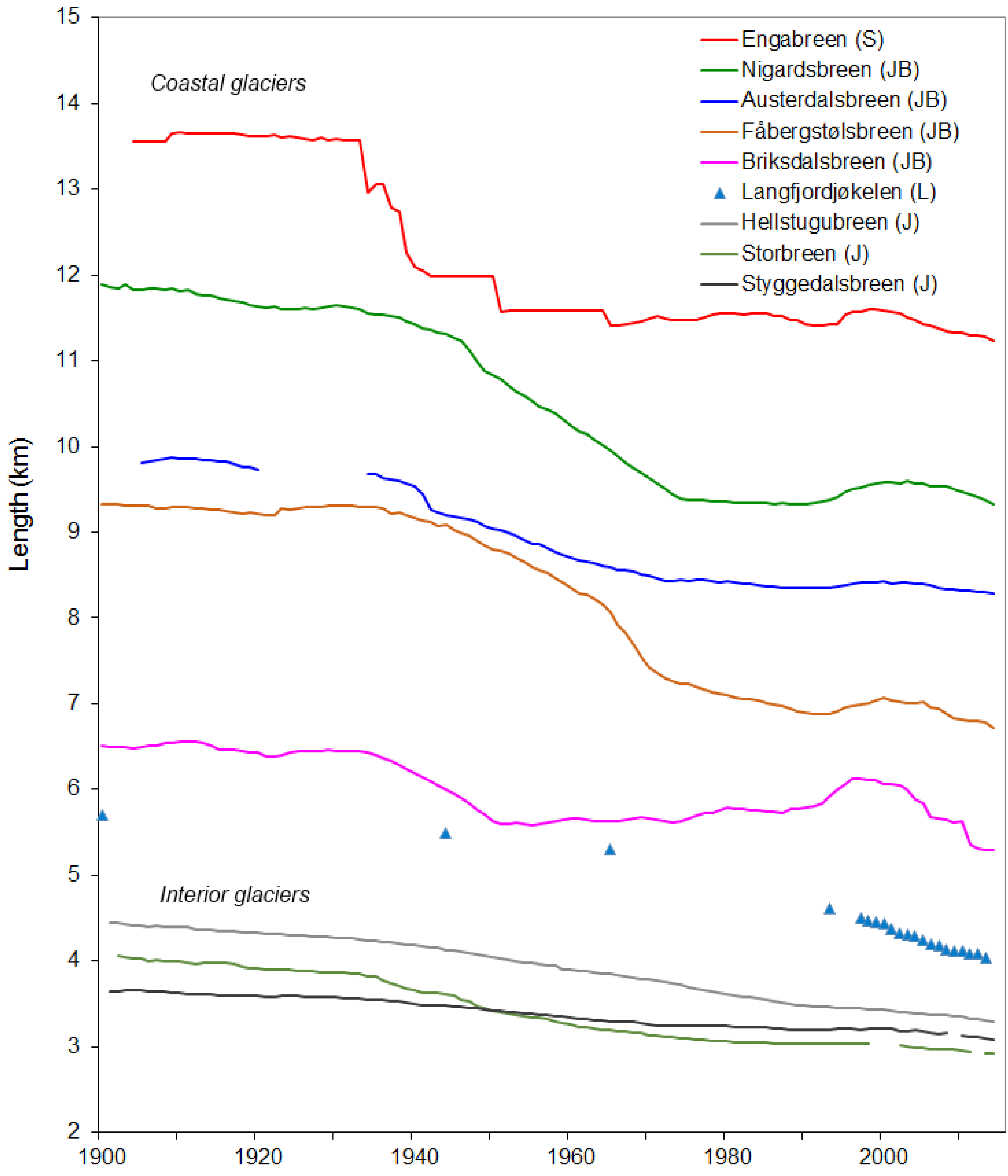
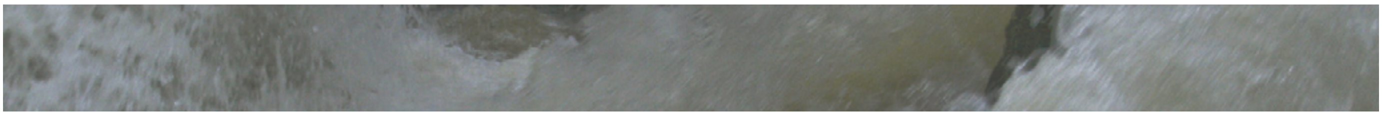


Figure 4.7 Changes in the position of glacier fronts in Norway from 1900 to 2014. The letter in brackets indicates the region where the glacier is located: S: Svartisen, JB- Jostedalsbreen in Sogn and Fjordane, L- Langfjordjøkelen in Finnmark, J-Jotunheimen in Oppland. Data: NVE



5. Permafrost, landslides and avalanches

5.1 Permafrost

By definition, permafrost is ground that remains frozen for two or more years. In Norway, permafrost is mainly found in the mountains and in some areas with mires. During the period 1981-2010, in total about 6 % of the land area had permafrost (Gisnås et al., 2013). Measurements show that permafrost has thawed and disappeared in some parts of Norway over the recent years. Thawing of permafrost is expected to further increase with increasing temperature. Modelling results for Southern Norway using the A1B emission scenario (IPCC, 2007), indicate that within 2050 permafrost with an annual average temperature of -1 to 0 ^{0}C (e.g. permafrost areas in Finnmarksvidda) will have thawed, and that by the end of the century permafrost in mountainous areas below 1800 m above sea level in Southern Norway will have disappeared.

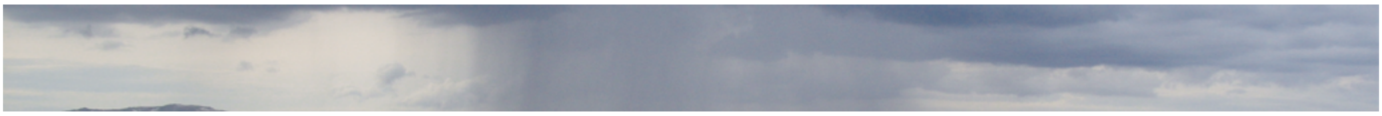
5.2 Landslides and avalanches

Landslides are separated into earth slides (including flood slides), rock slides and quick clay slides. Avalanches are - depending on the water content of the snow - separated into dry snow avalanches, wet snow avalanches and slush slides. Landslides and avalanches mostly occur in steep terrain. An exception is quick clay slides, which occur in lower lying areas below the marine limit (former sea bottom).

Snow avalanches and earth slides are, in particular, triggered by weather conditions, and temperature, precipitation and wind are variables that have a large effect on avalanche probabilities. Earth slides in steep terrain can be triggered by heavy rain and/or snowmelt. Quick clay slides are normally triggered by human activity, but can also be influenced by floods and erosion in small streams and in rivers. Smaller rock falls can be triggered by freezing and thawing, whereas large rockslides are very seldom related to weather conditions.

Because weather triggers certain types of slides and avalanches, climate change will affect their frequency (NGI, 2013; Jaedicke et al., 2008) as follows:

- Gradually increasing temperature will lead to a shorter snow season. The probability of dry snow avalanches will decrease because the altitude of the snow limit and of the treeline will gradually increase over time. However, the probability of wet snow avalanches and slush slides will increase, and these can occur in areas where they have not occurred previously.
- Increased precipitation and extreme rainfall in steep terrain will increase the likelihood of earth slides – including flood slides.
- Although most quick clay slides are triggered by human activity, increased floods leading to erosion under a future climate may result in more quick clay slides in certain areas.
- Smaller rockslides are often triggered by intense rainfall, and an increased frequency of such slides may be expected in the future. Large rockslides are mainly caused by long-term geological processes. Although thawing of permafrost may be a contributing factor, there is still not sufficient scientific evidence to conclude that climate change will have an effect on large rock slides.



6. Ocean climate including sea level

6.1 Oceanography

The ocean climate of the Norwegian Sea and the Barents Sea is largely determined by the inflow of Atlantic water (Østerhus et al., 2008). Both the volume and characteristics of this warm and salty water is important. Complex relationships exist between ocean and atmosphere, concerning both circulation and heat exchange. According to the Atlantic Meridional Overturning (AMO)-index (Sutton and Hobson, 2005) the Atlantic water was relatively cold about 100 years ago; relatively warm during the period 1930-1960 and cold during 1970-1980. After 1981, there has been a warming that now seems to have culminated. In addition to the inflow of Atlantic water, the ocean climate along the Norwegian

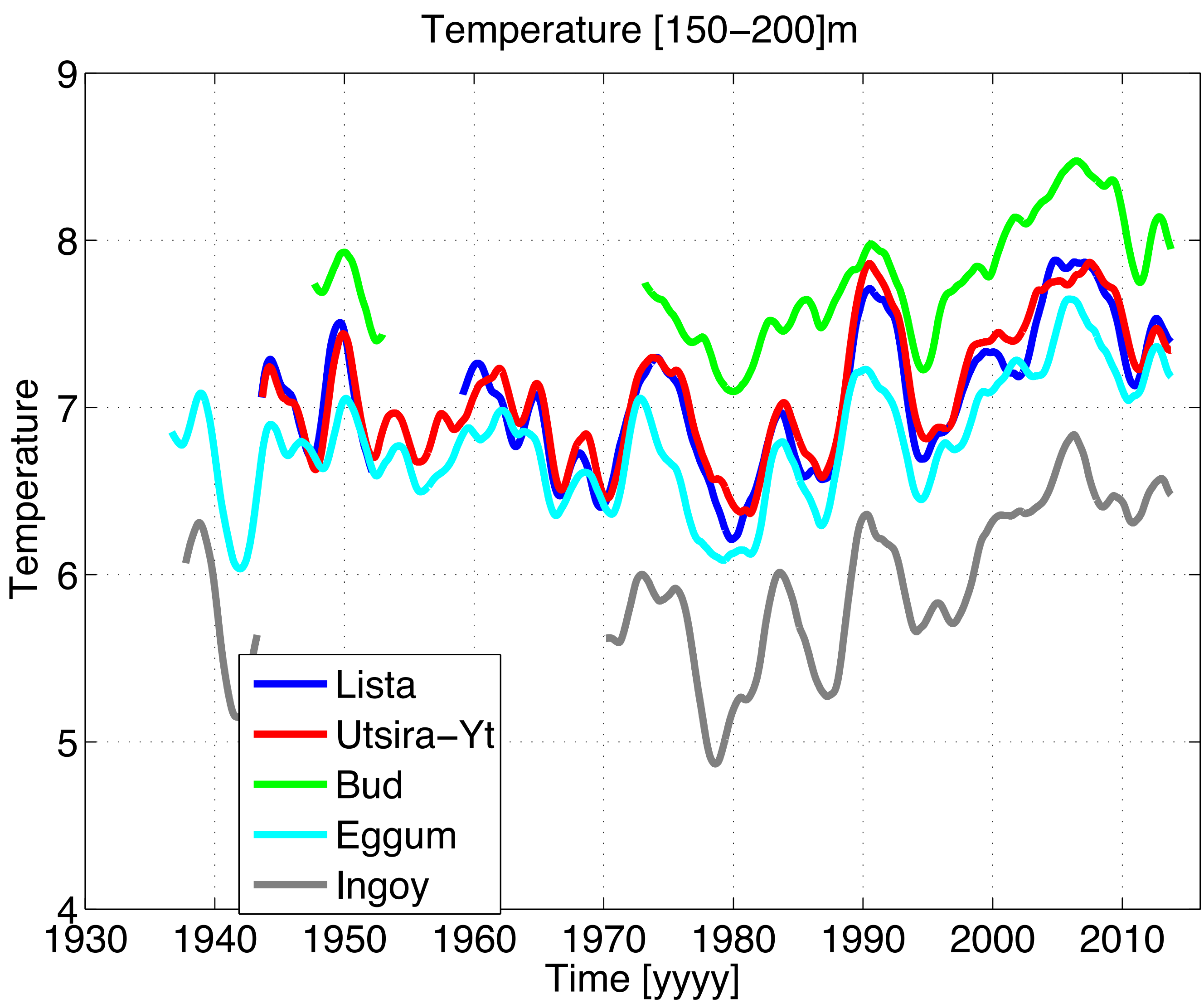


Figure 6.1 Variations in sea temperature (^{0}C) in the 150-200 m layer along the Norwegian coast from Lista in the south to Ingøy in the Barents Sea. The graphs are smoothed by a two-year filter.

coast depends on regional wind conditions and freshwater runoff. The Atlantic water gradually gets cooler and less salty on its way northwards because of mixing with the coastal current and Arctic water, as well as precipitation and heat loss to the atmosphere. The time variations still largely follow the Atlantic water, especially in the deep water (Figure 6.1).

The heat transport along the Norwegian coast and the vertical heat flux in the Barents Sea, which is connected to deep water production, are parts of the so-called Atlantic Meridional Overturning Current (AMOC), where warm and salty water masses are transported northwards near the surface, allowed to cool, then sink down and transported southwards in the deep. An increase in surface temperature resulting from global warming and a reduction in salinity due to melting ice, should lead to increased vertical stability, which would affect many ecosystem processes (Lien & Ådlandsvik, 2014). More stable water masses should also cause a weaker AMOC in the course of the 21st century (IPCC, 2013). However, so far direct observations show no signs of a reduction in AMOC or in the branch of the Atlantic stream into the Nordic seas (e.g. Skagseth et al., 2008).

The inflow of Atlantic water to the Nordic Seas, and especially to the Barents Sea, is not well simulated in the state-of-the-art global climate models (e.g. Langehaug et al., 2013). The question if, or to what degree, this can be "repaired" by regional climate modelling is not fully answered. Model results for the period 1997 - 2007 indicate a significant improvement of hydrography and sea ice extent in the Barents Sea (Sandø et al., 2014). For future climate, comparison of downscaled projections from two different global models, show consistent results for temperature, while the results for salinity differ a lot (Sandø et al., 2014). This indicates that unrealistic features from the global models may be transferred to the regional model results, thus adding to the uncertainty.

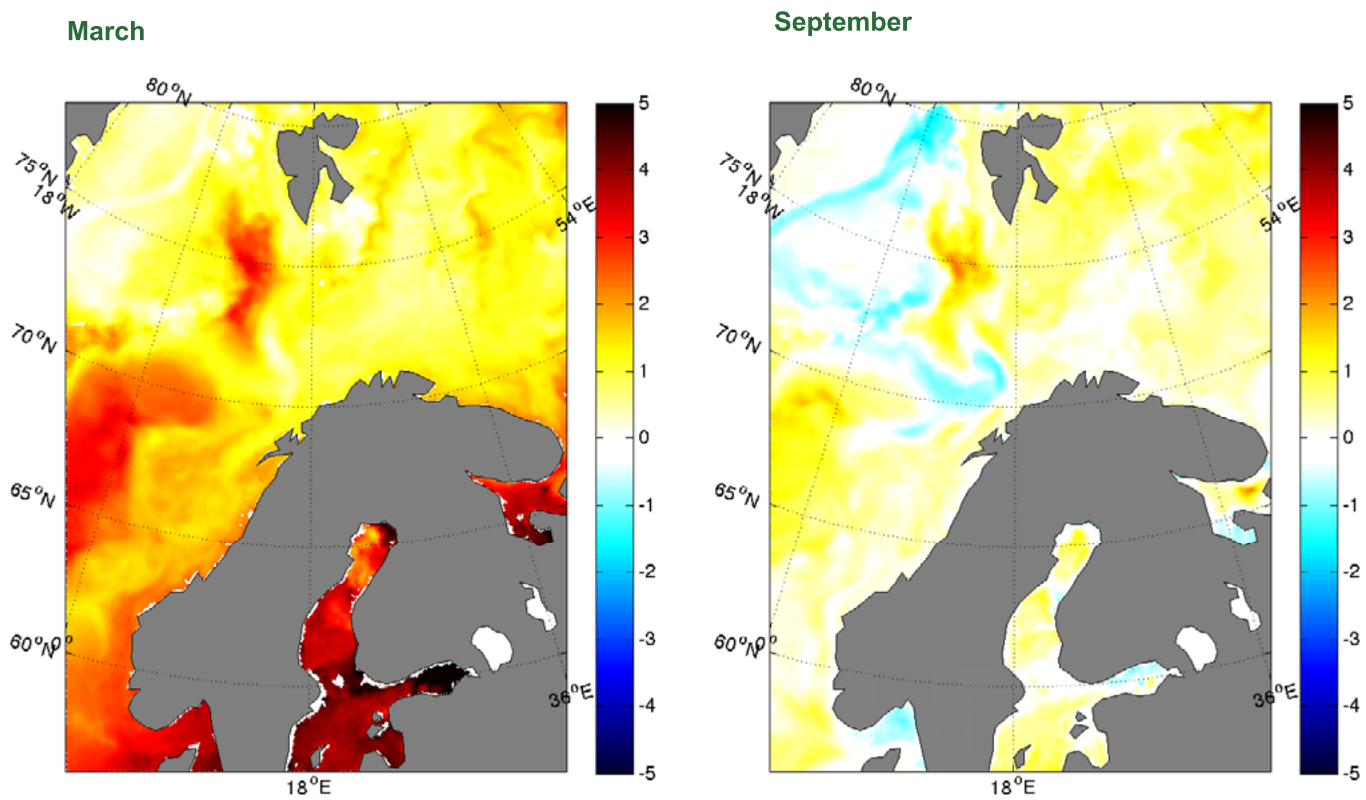


Figure 6.2 Changes in ocean surface temperature (°C) for March (left) and September (right) between2010-2019 and 2060-2069 under emission scenario RCP4.5. Results from the global model NorESM downscaled by ROMS (see Ch. 2.4).

The regional model ROMS (see Ch. 2.4) has been applied to downscale results from various global models and for different areas. Figure 6.2 shows modelled changes in ocean surface temperature between two 10-year periods, 50 years apart under emission scenario RCP 4.5, using the CMIP5 run from the global model NorESM. In the waters along the Norwegian coast, the greatest increase in temperature in the next 50 years (+3-4 °C) is simulated in the Oslofjord and the Baltic Sea in late-winter. Significantly smaller changes are simulated in late summer (Figure 6.2). The larger temperature increase in the Barents Sea (+1 °C in 50 years at average; up to +2 °C in eastern parts) is also simulated in late-winter. The modelled changes in the upper water masses, as well as changes in the ice conditions (Section 6.3), can result in large changes in the plankton production, and thus for the rest of the ecosystem (IPCC, 2014).

Note that the application of 10-year time slices in this experiment makes the possible effect of natural variability significant. Further, the degree of future warming will depend on feed-back links in the climate system. A possible such link is related to the increased heat transfer into the Barents See, which would lead to reduced sea ice cover, greater heat fluxes to the atmosphere, increased deep water formation, increased export of deep water to the Arctic Ocean, and hence increased inflow of warm Atlantic water. Experiments with the Bergen Climate Model support this feed-back (Smedsrud et al., 2013).

Despite of several sources to uncertainty, the model results given above are largely in accordance with other results from regional modelling based upon CMIP3 and CMIP5, especially during winter. For summer conditions, the results diverge somewhat more, probably due to differences concerning sea ice extent in the models.

6.2 Ocean Acidification

The average pH in the surface of the world's oceans has decreased by 0.1 from around 8.2 before the industrial revolution to the present average of around 8.1 (Orr et al., 2005). Note that the pH scale is logarithmic, so this is a considerable change, corresponding to a 26% increase in hydrogen ion concentration (IPCC, 2013). Surface water from the North Atlantic entering the Nordic Seas today is in equilibrium with the atmospheric content of CO_2 (Olsen et al., 2006). A time series of carbon chemistry from a station in the Norwegian Sea (66°N, 2°E) showed an annual change in pH of -0.001 pH units per year in the surface waters between 2001 and 2005 (Skjelvan et al., 2008). Surface waters in the Arctic Ocean have low temperatures and high natural concentrations of non-organic carbon. They are expected to be under-saturated with respect to aragonite within ten years (Steinacher et al., 2009). By using the downscaled physics from a climate model, a comparison is carried out of the simulated carbon exchange in 2000 and 2065 in the Nordic sea and the Barents Sea under emissions scenario A1B (Skogen et al., 2014). The simulated pH-value in the surface change with about -0.2 from 2000 to 2065, while the atmosphere-sea flux in the Barents Sea is increased from 23 to 37 °C per m^2 per year.

6.3 Sea Ice

The observed reduction in Arctic sea ice is one of the most significant signs of climate change in the Arctic (Ivanova et al. 2014). The main changes are that (i) the sea ice extent has decreased for all months of the year, mostly for September-October, (ii) the proportion of perennial ice is significantly reduced, which causes that (iii) the average ice thickness is significantly reduced, since the greater part of the ice cover consists of first-year ice, which is typically 1-2 m thick. These changes have also led to an increase in both mean speed of sea ice drift and the melting season length.

State-of-the-art climate models also simulate reduced sea-ice cover and thickness in the Arctic during the latest decades, but there is a considerable spread in the results, and a majority of the models show a smaller reduction than what has been

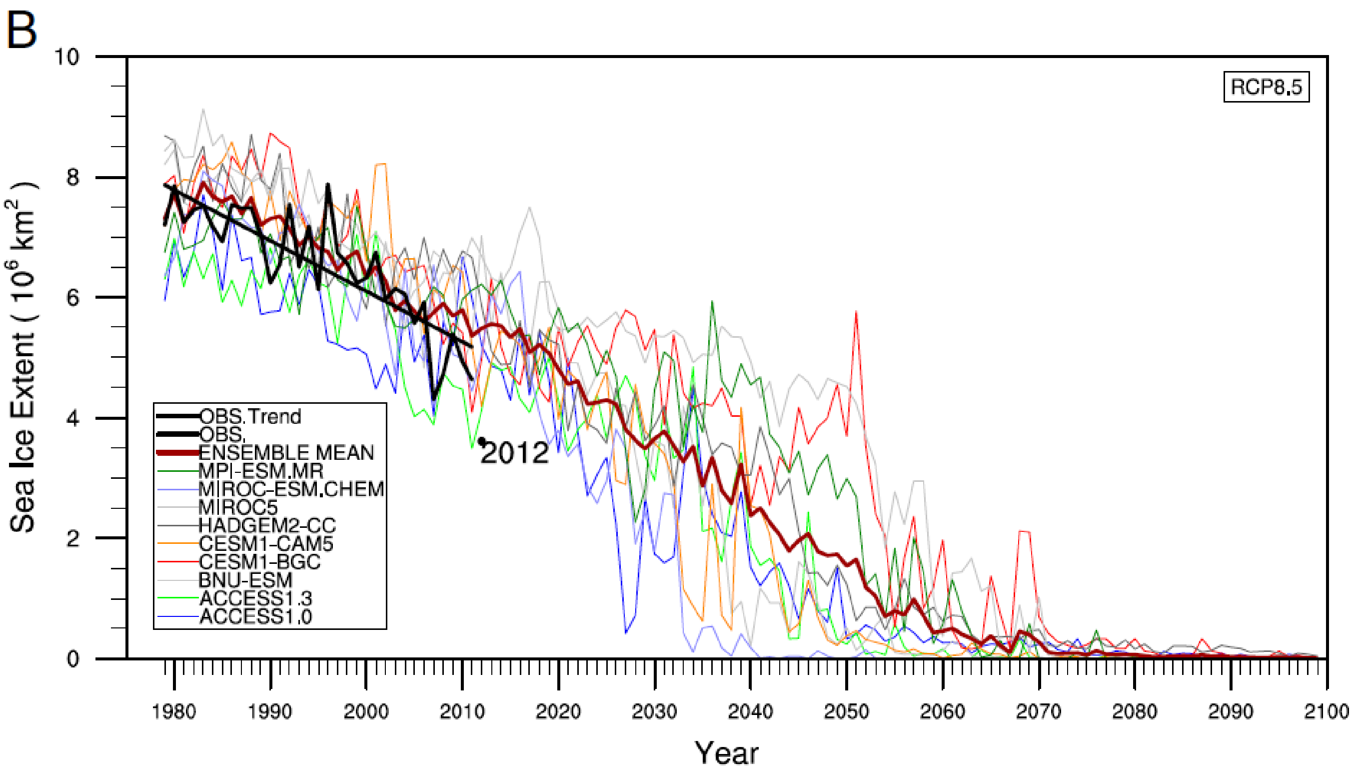


Figure 6.3 Estimated future reduction in September sea ice extent based on 9 different climate models (colored curves) under RCP8.5. The thick red curve shows model average, while black curve shows observed sea ice extent based on satellite data. The figure is taken from Liu et al., (2013).

observed. Liu et al. (2013) selected nine models that were most in agreement with the observations, and applied them for projecting changes in sea-ice towards the end of the 21st century. Under RCP8.5, these models indicate an "ice-free Arctic" (less than 1 million km^2 sea ice) in September 2054–2058 (Figure 6.3). The future reduction in sea ice may enable new routes for shipping traffic in the Arctic summer. In winter, these routes are not available, as no climate model simulates an ice-free Arctic in winter by 2100.

6.4 Sea level

During the last glaciation the global sea level was about 120 m lower than today, because water was tied up in large ice caps. Approximately 4,000 years ago the world's ice masses had melted down roughly to the current size, and the global sea level has since then remained more or less constant until the last century. The relative sea level in Norway has mainly decreased in this period, because of the continuing land rise after the Ice Age. Dynamic effects including currents and wind systems can give significant short-time deviations from the long-term trends.

The sea level off the Norwegian coast is calculated to have increased on average by 1.9 mm per year in the period 1960-2010. During the period 1993-2014, the average increase was about 3.8 mm per year. Thermal expansion of the ocean and melting of the world's glaciers and ice caps are the main reasons for this. Different land rise rates in different parts of Norway after the last Ice Age, results in differences in observed sea level changes for different locations. For the period 1960-2010 the observed sea level changes range from -12 cm in Oslo to +5 cm in Stavanger (Simpson et al. 2015). Measurements from recent decades indicate that sea level rise has accelerated significantly.

Calculations and thorough analyses of local sea

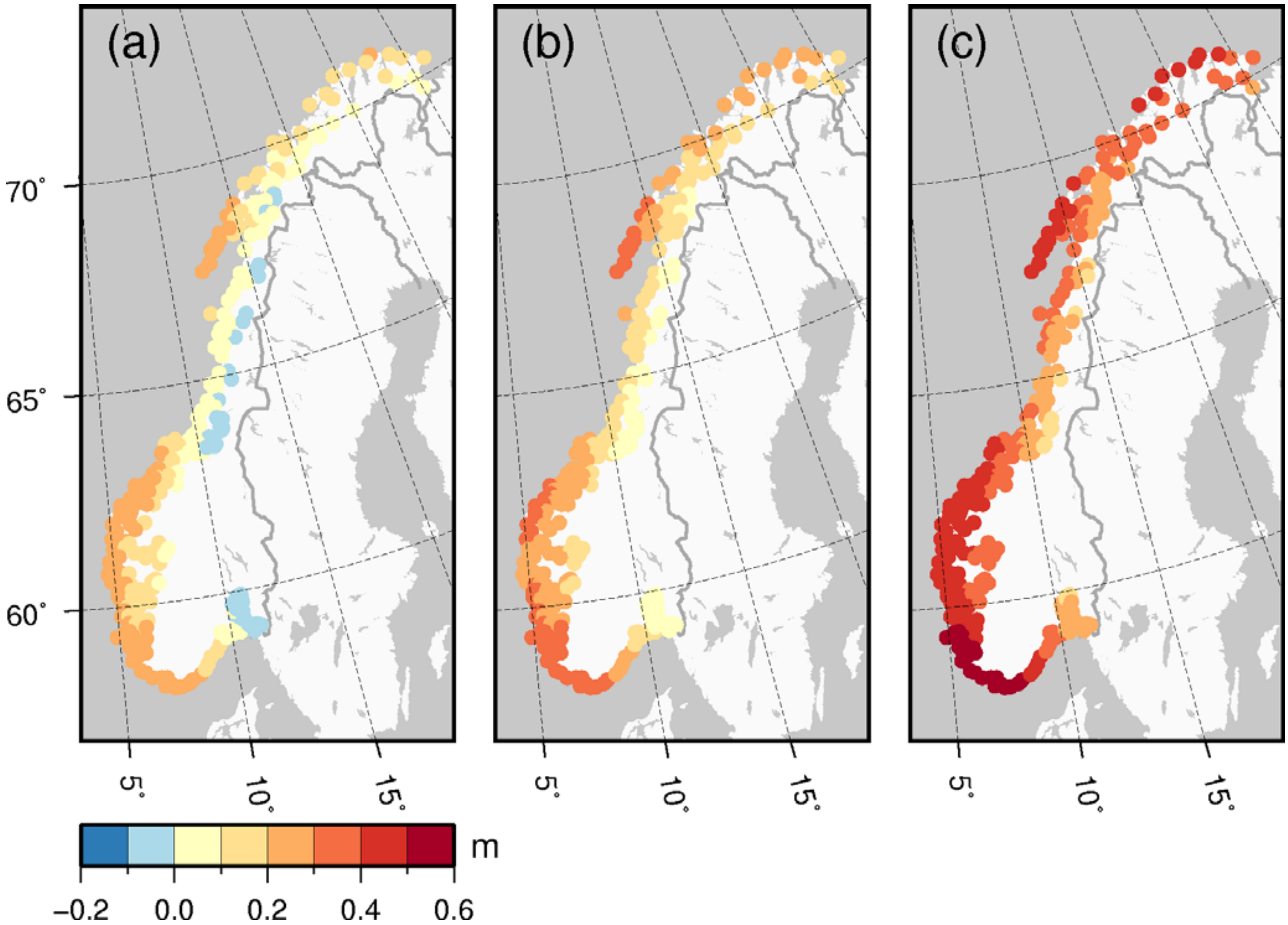


Figure 6.4 Projections (model average) of changes in relative sea level in Norway from 1986-2005 to 2081-2100 for a). RCP2.6, b). RCP4.5 and c) RCP8.5. From Simpson et al. (2015).

level projections for the Norwegian coast for the 21st century under various emission scenarios were published by Simpson et al. (2015). The average projections (Figure 6.4) indicate that most of Norway will experience rising sea levels before the end of this century. For RCP2.6 the mean projection give a change in sea level during 100 years in the interval -10 to +30 cm depending on location. For emission scenario RCP4.5 the interval is 0 to +35 cm and for RCP8.5 the interval is +15 to +55 cm. The report also includes uncertainty intervals based on the 5- and 95-percentiles.

Extreme sea levels usually occur in connection with storm surges. Projections of storm activity are uncertain, and are thus not taken into account. Still, it is necessary to combine climate projections with the probability density function for extreme values. Simpson et al. (2015) have done this by application of "Hunters method" (Hunter, 2012). The generally increased sea level is projected to lead to considerable changes in the 20, 200 and 1000 year return heights. E.g. the 200-year return height in Stavanger based upon the reference period 1986-2005 is projected to be exceeded in four out of ten years during the present century (Simpson et al., 2015).

7 Assessment and use of projections

7. 1 Uncertainties related to the climate projections

Climate projections are uncertain for several reasons. Uncertainties are related to 1) future anthropogenic emissions, 2) natural climate variations and 3) climate models.

1) Uncertainties related to future anthropogenic emissions are largely due to uncertainty in future economic activity, global population increase, choice of energy sources, energy efficiency and other socio-economic factors that to a certain extent are politically driven. In this report these uncertainties are taken into account by using and presenting results for 2-3 emission scenarios.

2) Uncertainties related to natural climate variability are partly due to internal mechanisms that redistribute the energy geographical or between the sea and the atmosphere, and partly to the fact that future changes in the natural climate forcing (e.g. solar radiation) are unknown. Manifestations of such variations on the trends in the climate over the last 100 years are - on the global scale - small compared to several of the other uncertainties that are discussed here. Internal variations may, however, provide significant regional climate variations, and lead to great uncertainty in local climate. The uncertainty can be mapped by the use of multiple model runs with the same emission scenario but with different initial conditions.

In this report, uncertainty connected to natural climate variability is partially taken into account as internal climate variations to a large extent is simulated by climate models, and the use of multiple models provide a picture of this uncertainty. Variations in the natural climate forcings are, however, not taken into account. If they do not exceed their level during the last 100 years, they will still have relatively little impact.

3) Model uncertainty is related to shortcomings in our understanding of the climate system, as well as limited ability to implement the understanding in a numeric mathematical framework and limited capacity of supercomputers. Limited computer capacity leads to the need for parameterization and simplified descriptions of processes. Uncertainties related to the parameterizations can be mapped by running many simulations of the same model, but with different parameter settings (Perturbed Physics Ensemble (PPE)). Calculations with the same emissions scenario, but different climate models (so called Multi Model Ensemble (MME)) can provide a picture of uncertainty related to various process descriptions. Neither PPE or MME will embrace the uncertainties caused by the common deficiencies and errors, e.g. processes that are not in any model.

The uncertainty related to climate models' error and simplifications, is to some extent taken care of by using MME, because different models have different errors and simplifications. PPE is not used here for climate models, but is utilized in the hydrological modeling, where 25 different parameterizations are included.

To calculate the local climate changes and their effects on hydrology, it is necessary to post process the results from climate models and use them as input in hydrological models. This will introduce additional uncertainty in the derived variables. This uncertainty can be mapped by using several methods and parameterizations in post processing and impact models.

For oceanographic variables uncertainty is not estimated as the number of available projections is very limited. For meteorological and hydrological variables, climate change is specified by a median value and an uncertainty interval based on the 10th- and 90th-percentiles in an ensemble of climate projections. For sea level, the uncertainty interval is based on the 5th- and 95th-percentiles.

Uncertainty connected to processes that we do not know, or that are poorly described in all climate models are not taken into account, and may thus lead to results outside the intervals defined by the model based percentiles. An example of poorly described processes is dynamical processes in ice sheets. A collapse of ice masses in Antarctica or on Greenland might thus lead to sea level rise beyond the 95th-percentile given here.

Another possible weakness in the climate models is seen in the fact that none of them reproduce the historically observed relation between increase in precipitation and temperature in Norway. Based on observations during the last 100 years, the increase in precipitation was 8-11 % per 1 °C warming. This is slightly above the theoretical 6-8 % increase per degree C according to the Clausius-Clapeyron relationship. The projected precipitation increases during the 21st century are, however, significantly lower. Linear regression based on all models and for periods around the mid-century as well as towards year 2100 suggests that one degree increase in temperature leads to a 3.4 % increase in annual precipitation. This discrepancy is not fully understood, but indicates a possibility that climate model results for Norway underestimate the response from temperature increase on precipitation.

7.2 Recommendations

Future emissions of greenhouse gases and pollution particles are largely influenced by governmental decision making. It is thus not possible to say which emission scenario is most realistic. For different emission scenario this report presents median values as well as intervals including 80 to 90 % of the model results for various climate variables. However, this maps only part of the total uncertainty, and it cannot be ruled out that future climate will end up outside the model spread. The results should therefore be considered in relation to their application. If they are used for risk assessments, projections should be chosen according to the seriousness of the consequences. For the use of climate projections in research and management it is recommended that the relevant scientific communities are contacted.

For the next 10-20 years, natural variations will largely dominate over the “climate signal” resulting from enhanced greenhouse effect. As outlined in Ch.1.3, it is therefore recommended that for planning of adaptation measures or buildings and infrastructure with a lifetime limited to the next few decades, statistics based on the latest 30 years are used rather than downscaled results from climate model simulations.

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