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Climate change and natural disasters in Norway

An assessment of possible future changes

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Abstract

The Norwegian Agricultural Authority (Statens landbruksforvaltning, SLF) is due to make new legislation on safeguarding and compensation for natural disasters and hazards, and has requested an updated assessment of whether the projected climate changes will make the Norwegian society more or less vulnerable to natural hazards in the next 30–50 years. The main results are described in a report (in Norwegian) to SLF («Utviklingen av naturulykker som følge av klimaendringer»). The present report provides the scientific background for the conclusions in the report to SLF, and addresses the extent to which changes are expected in Norway in frequency, extent and magnitude of damages associated with natural hazards under global warming.

The main types of natural hazard events discussed are changes in: precipitation, flooding and ice jams, strong winds, sea level and storm surges, avalanches and slides, permafrost, other hazards (e.g. earth quakes, tsunamis, sub sea slides) and the society's vulnerability to natural hazards and disasters.

This assessment is made in collaboration between several Norwegian institutions: met.no (Norwegian Meteorological Institute, main responsibility for the assessment); Cicero (Center for International Climate and Environmental Research); ICG/NGI (International Center of Geohazards/Norwegian Geotechnical Institute), NGU (Geological Survey of Norway), NVE (Norwegian Water and Energy Resources Administration).

Keywords

Climate change, natural hazards, society's vulnerability to natural hazards,

Disciplinary signature Eirik J. Førland	

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Preface and summary

Excerpts of the mandate for natural disaster assessment

The Norwegian Agricultural Authority (Statens landbruksforvaltning, SLF) is due to make legislation on safeguarding and compensation for natural disasters and calamities[1], with a full reference of the background and objective of the national natural calamity management. In this context, it is important to have sufficient knowledge about weather and climatic conditions and the vulnerability of the Norwegian society.

The SLF has ordered an assessment of the up-to-date knowledge on weather and climate conditions and projections for the next 30–50 years. The assessment must address the question of how the future occurrence and magnitude of natural disasters may be affected be a climate change and provide a comparison with historical statistics. Moreover, the objective is to asses whether a climate change will make the society more or less vulnerable in terms of natural disasters/calamities in the next 30–50 years.

For the present situation, the natural calamity management focuses on flooding, storms, avalanches, and landslides. Therefore, the assessment addresses these types of events. Important questions are:

- Can we expect more extreme rainfall causing water catchments/rivers/brooks to flood?
- Do climate changes entail greater snow pack as well as more rapid melt-off, leading to severe ice runs and higher risk of flooding?
- Can we expect more frequent wind speeds exceeding 20.8 m/s?
- Does the frequency of combined spring tide and storm surge increase?
- Will the risk increase for greater snow accumulation and avalanches.
- Will the frequency of other forms of landslides increase?

The question whether damages linked to other natural disasters such as earth quakes, tsunamis, or sub-sea landslides will become more frequent is discussed only very briefly. Likewise permafrost and associated damages are only described concisely, and land heave and droughts are not regarded as relevant in terms of the national natural calamity management.

The assessment aims to address the extent to which changes are expected in frequency, extent, and magnitude of damages associated with natural disasters/calamities. As mentioned in the mandate attached to the letter from SLF dated December 20th, 2006, the following key points are elucidated:

- If a higher incidence of natural calamities/disasters can be expected as a result of changes in the weather statistics.
- If more extensive natural disasters can be expected.
- If the geographical distribution of natural accidents will be altered.
- If the link between natural calamities/disasters and causes will change.

1) *http://www.sdpi.org/help/research_and_news_bulletin/sept_oct_05/investing.htm*

Description of the strategy of the assessment

The latest IPCC (2007) results indicate that the global temperature is projected to increase by between 1.0 and 6.3 ºC up to year 2100, based on different global climate models and with different scenarios for emission of greenhouse gases and aerosols. The large spread is partly due to internal variability as well as the differences between the emissions scenarios for greenhouse gases. In the Norwegian RegClim project *(http://regclim.met.no)*, data from global climate models are downscaled by dynamical and empirical methods to provide scenarios for regional and local climate changes in Norway for the next 50–100 years. Most dynamically downscaled scenarios for Norway represent the 2071–2100 period, but some projections describe the 2030–2050 period compared to 1980–2000. Empirical-statistical downscaling, on the other hand, tends to describe the total 2000–2100 interval.

It is essential to bring in facts about natural disasters for the legislation of a new Norwegian law on natural calamities, and hence questions whether climate change may influence the vulnerability of the society during the next 30–50 years need to be addressed. In Northern Europe, the climate conditions are influenced by large natural variability, both on inter-annual and decadal time scales. Random internal variations may dominate over regions like Scandinavia during the next 20–30 years, however, systematic changes caused by changes in radiative forcings will become more pronounced after that. Analyses of the climate development over Scandinavia must therefore include regional internal fluctuations in addition to the large-scale global warming.

The development and intensity of the extra-tropical cyclones may often result in extreme weather conditions and natural disasters in our region. These are formed and developed over the North-Atlantic and in the prevailing westerlies. Moreover, the cyclonic activity is crucial for extreme precipitation and wind events in Norway. During the latest 30–40 years there has been a substantial change in the cyclonic tracks, which may explain a large part of the «unusual» weather types over the Nordic region. Unfortunately it is not possible to state whether this is caused by global warming or whether it is a natural variation which would have occurred anyway. It is however a fact that the recent development in many aspects resembles features predicted by the climate models.

The assessment will consider the variability in occurrences of natural disasters and climatic extremes for the latest 50–100 years in order to relate the magnitude of the projected climate changes for the next 30–50 years with the actual historical climate variability. The main reference period used is the climatologically «standard normal period» 1961–1990. Observations from this period are the basis for a large number of dimensioning values for average and extreme climate elements.

All kinds of landslides are caused by weather or climate, but other factors may also play a role. Debris flow triggered by flash floods in river beds is one example where intense rainfall may be linked to such landslides when downpour exceeds critical thresholds within short intervals (~hour). Extensive avalanches are triggered by weather conditions during several days. An unstable layer in the snow may be formed over prolonged periods under right conditions, and high snowfalls on top may then cause a collapse. By studying the link between landslides and avalanches on the one hand and weather on the other, it is possible to elucidate how the frequency of such events may be affected by a climate change. This type of analysis is addressed in the ongoing project GeoExtreme (*www.geoextreme.no*).

Summary

This report aims to address the extent to which changes are expected in frequency, extent and magnitude of damages associated with natural disasters and hazards in Norway under global warming. The Norwegian Agricultural Authority (Statens landbruksforvaltning, SLF) is due to make new legislation on safeguarding and compensation for natural disasters and hazards, and has requested an updated assessment of whether the projected climate changes will make the Norwegian society more or less vulnerable to natural hazards in the next 30–50 years. The main results are described in a report to SLF in Norwegian («Utviklingen av naturulykker som følge av klimaendringer»), and the present report provides the scientific background for the conclusions in the report to SLF.

The main questions from SLF were:

- Whether a higher incidence of natural disasters and hazards can be expected as a result of projected climate changes in Norway
- Whether more extensive natural disasters can be expected
- Whether the geographical distribution of natural hazards will be altered
- Whether the link between natural calamities/ disasters and causes will change

The main types of natural hazard events SLF wanted elucidated were changes in: precipitation, flooding and ice jams, strong winds, sea level and storm surges, avalanches and slides, permafrost, other hazards (e.g. earth quakes, tsunamis, sub sea slides) and the society's vulnerability to natural damage.

Precipitation: The scenarios indicate a weak increase in extreme rainfall over large parts of Norway during the next 25 years, and a stronger increase up to year 2050. The projected increase is largest in parts of Western Norway and the counties of South Trøndelag and Nordland. For south-eastern Norway the scenarios indicate just small changes in extreme 1-day rainfall during the next 50 years.

Floods and ice jams: The scenarios indicate that the large snowmelt floods in major rivers, with high potential of flood damage to infrastructure on the flood plain, is likely to be reduced because of reduced snow volumes. The snowmelt floods will occur earlier in the spring than in the present climate. However, the inter-annual variability is large, and there may still be a few years with large snow volumes and potential for extreme snowmelt floods. Late autumn floods and small winter floods will become more common. The projected increase in extreme local high-intensity rainfalls may cause severe flash flood events in inland and urban areas. According to the climate projections, there will be more ice runs which may jam at new places. There will be an increased area along the coast with seldom ice, and longer stretches free of ice downstream in large lakes. Increased glacier melting will lead to a substantial increase in summer stream flow in the glacier rivers .

Strong winds: There are pronounced inter-annual and inter-decadal variations in the frequency of wind speed exceeding the threshold value for strong gales, but geostropical wind analysis of long sea level pressure records does not give any evidence of significant long-term trends since 1880. Scenarios for future wind conditions do not suggest any clear tendencies for the next 50–100 years, although several studies indicate that the most intense mid-latitude storms nevertheless may become more frequent in a warmer climate.

Sea level and storm surges: Along the Norwegian coast the global increase in sea level height will be ameliorated by the continental uplift in Scandinavia. Thus it is conceivable that there will be no net change in mean sea level height (SLH) at most locations along the Norwegian coast in the next 50 years. But if the SLH rise is larger than 0.5 m, significant increases in SLH will be evident at all locations along the coast. The evidence for changes in variability and frequency of extreme events is weak, and a future increase in extreme storm surge events is therefore dependent of increase in SLH.

Avalanches and slide events: The frequency of recorded slides (avalanches, debris slides and rock slides) has increased exponentially in Norway since 1960, but this was found to be mostly due to human factors. Snow avalanches are the slide type causing the highest number of casualties. The projections of future changes in slide frequencies are tentative, but it seems as if the southern coastal regions may expect a moderate to strong increase. In inland regions and the northern coastal regions a small increase in slide frequency is projected.

Permafrost: The mountain regions in Norway have an extensive amount of permafrost. At present the permafrost is warming considerably. It is evident that if the observed ground warming proceeds or even accelerates, major changes in mountain permafrost distribution in Norway will be anticipated through the 21st century.

Earth quakes, tsunamis, sub sea slides, etc.: Climate change will most probably not cause any changes in frequency of earth quakes or sub sea slides. Permafrost degradation in steep bedrock slopes can lead to increased instability. If this leads to more

rock slides in steep bedrock slopes, the risk of flood waves (tsunamis) will increase in some fjord and lake districts.

The society's vulnerability to natural damage: The analyses at the regional level give some indications of expected trends, but the information is not detailed enough to indicate where the vulnerability will be greatest and to which type of natural hazard. Generally the climate scenarios indicate that there will be an increase in all weather types that may trigger natural hazards. There is not necessarily a correlation between high assessed costs and the magnitude of the natural hazard; a major natural hazard (e.g. an avalanche) in an area with little infrastructure and few buildings can have an assessed damage cost close to zero, while a smaller natural hazard in a densely populated area can have high assessed damage costs. It is crucial to adapt the society such that the scope of damage is kept to a minimum. Investments in protection, good land-use planning and good building practices are all important elements to limit the damage from natural hazards.

Uncertainty: Several sources of uncertainty are linked to scenarios for future climate development. The most important are: a) Internal variations in the climate system leads to unpredictable natural variability, b) Uncertainty on future changes in climate forcings (Natural forcings as solar radiation and volcano eruptions and anthropogenic release of gases and particles), c) Imperfect climate models (Imperfect knowledge about forcing and processes; imperfect physical and numerical treatment of processes; poor resolution in the global models), d) Weaknesses in downscaling techniques. Simulations with different climate models and emissions scenarios may therefore give different projections. Particularly large uncertainty is linked to extreme events at specific localities; i.e. the weather events that may trigger the types of natural hazard described in this report.

1 Introduction

The global climate for specific time periods is described partly by global mean values and partly by typical variations between different regions. The nature, and traditionally also the society, has through generations adapted to the climate in the region they belong. Climatic differences can consequently explain many contrasts between different regions in flora and fauna as well as in building standards, culture and trades. Neglecting risks for damages caused by extreme weather may lead to poor adaptation to local climate conditions. Buildings placed to get a nice view may be exposed to strong winds. Urbanisation may lead to increased risk for flooding because of widespread asphalt, deforestation and removal of creeks. Changes in damages caused by bad weather may therefore not just be caused by global climate change.

General background about extremes

Characteristics for extreme weather and climatic events are that they occur infrequently and involve severities normally not experienced. Extremes may include storms, strong wind gusts, very heavy precipitation, droughts, long and very wet spells, very hot or cold days, lightening and hail, or tornadoes. The fact that extremes are rare, have a local effect, and are severe and sometimes difficult to measure, can be an obstacle to collecting good statistics describing how they change over time. This problem was encountered in a study of intense historical storms over Norway in connection with forest damage and bark beetle outbreak: only a small number of events with sufficient intensity to cause wide spread forest damage are documented. A larger sample is needed for a statistical analysis. Furthermore, very intense but ephemeral local events are not measured because they do take place between the observing stations. Heat waves and droughts, on the other hand, tend to involve greater spatial extents and are more easily measured and quantified, thus allowing a better statistical basis.

It is important to appreciate the kind of information on which our knowledge about extreme weather and climatic events is based. The underlying information can be regarded as consisting of three pillars: empirical data, analytical methods, and theory (physical laws). It is tricky to draw conclusions about extremes just from one type information, since even for purely theoretical considerations, empirical data are needed to make the results relevant for the real world. Another aspect is whether it is possible to learn from the past since a climate change implies a change in the statistics. Global climate models, which are based on physical laws also use empirical data from the past in order to provide a complete picture of our climate, and represent one important tool for making climate scenarios. The computational capacity is limited, and it is therefore not possible to make long simulations of the climate with the high spatial resolution needed for the details important for many extremes. It is nevertheless possible to use regional climate models with a high resolution for a limited area to study the finer climatic details.

When it comes to empirical data, time series from observations at meteorological stations are often used. However, the observational network is often intended for the study of mean conditions, where the spatial coherence is stronger than for some extremes. If an extreme event has a very local extent, then there is a risk that this event is not captured by the observational network, or that only one station records the event. The analytical methods are often set up to discard errors and spurious data, for instance by excluding suspicious 'outliers' as these can have a strong influence on the results. But such outliers may also be real, and may then provide very important information about the extreme statistics. Thus, abundancy, at least to some degree, is needed to ensure that outliers are real. This implies that a dense network of observing stations is required for the study of some extreme events; in addition to long time series.

Changes to the ocean circulation

Changes in the ocean circulation associated with the Gulf Stream extension into the Nordic Seas (the thermohaline circulation, THS) may result in changes in the storm track, since the regional north-south temperature profiles are expected to change as a result. However, the global climate models have not given strong indications for substantial changes in the THS. So far, these models only have a coarse spatial resolution and are not able to adequately represent the detailed characteristics of the narrow ocean currents.

Such changes are likely to have consequences for sea surface and land temperatures as well as the sea-ice extent. Sea surface temperatures (SST) and sea-ice exhibit a (weak) statistical link with precipitation, and it is therefore plausible that a substantial change in the local sea conditions may influence the extreme precipitation. Benestad & Melsom (2002) have identified a possible connection between SST in the North Atlantic and monthly rain fall statistics.

According to the latest IPCC (2007)-report that «it is *very likely* that the Atlantic meridional overturning circulation (MOC) will slow down during the 21st century, with an average model-estimated reduction by 2100 of 25 % (range from zero to more than 50 %). Temperatures in the Atlantic region are projected to increase despite such changes due to the large warming associated with projected increases of greenhouse gases. *It is very unlikely* that the MOC will undergo a large abrupt transition during the 21st century. Longer-term changes in the MOC cannot be assessed with confidence.»

Data and Methods

All climate data required for the assessment of the conditions described in the mandate are provided by the Norwegian Meteorological Institute. Historical data (1900–2005) are taken from the met.no climate data base, and the climate scenarios are mostly based on the results from the RegClim project and the downscaling of a global climate scenario based on the ECHAM4/OPYC3 climate model from the Max Planck Institute for Meteorology in Germany and HadCM3 from the Hadley Centre in the U.K. The global climate scenario represents the intervals 1980–2000 and 2030–2050 and follows the IPCC emission scenario IS92a for dynamical downscaled results. In order to present more than just one scenario and obtain an idea of associated uncertainties, the results for the 2071–2100 period are also discussed. The difference between results from the different climate models provides some information about regional differences in the storm track location. In addition, some results are based on empirical downscaling of more recent results (IPCC, 2007) based on more than 20 different climate models following the IPCC SRES A1b scenarios.

As of today, about 30,000 avalanches and landslides are recorded digitally in Norway, and this data base is managed by various governmental and private organisations. These events have been collected and organised in one common data base for the GeoExtreme project by NGI. The data base contains information about individual events, including at least time, location, type of event. In addition, other relevant parameters are included such as injuries and damage on built environment. The event register is initially used to investigate trends and variability in frequency since 1960. Subsequent analysis involves linking these events with weather situations based on data from the met.no climate data base in order to examine any possible weather-related triggering factors. Furthermore, statistical analyses are employed to identify which weather parameters are important for initiating the different types of avalanches or landslides, and climate models will provide the basis for estimating how these parameters may change in the future according to various climate scenarios. These projections are used to quantify the degree the frequency of avalanches and landslides may be affected by a climate change.

2 Observed and projected changes in extreme precipitation

(Eirik J. Førland, Eli Alfnes, Rasmus Benestad, Torill Engen-Skaugen, Inger Hanssen-Bauer and Jan Erik Haugen, met.no)

Key points

- The annual precipitation in Norway has increased between 0.3 and 2.1 % per decade in different parts of Norway during the latest 100 years. The largest increase has occurred in Western-Norway and large parts of Central and Northern Norway.
- In Western Norway there has been a weak tendency of increasing 1-day rainfall extremes during the later decades. In the other parts of the country there has been very small changes.
- Up to year 2050 the downscaled scenarios project an increase in average annual precipitation of 0.3 to 2.7 % per decade in different parts of Norway. The largest increase is projected in north-western and western regions.
- The projections indicate a small increase in extreme rainfalls for the next 25 years, but with a stronger increase during 2025–2050. The projected increase is largest in parts of Western Norway, and in the Sør-Trøndelag and Nordland Counties.
- For all of Norway the scenarios indicate that daily rainfalls that are considered extreme today will be more common in the future.
- Also for monthly precipitation more extreme values can be expected, especially during winter, spring and autumn.

2.1 Observed changes in extreme precipitation in Norway

(Eirik J. Førland and Eli Alfnes, met.no)

An increase in the annual precipitation has been observed during the last century at higher northern latitudes (Folland, et al., 2001). According to IPCC-TAR (Folland et al., 2001) it is likely that there has been an increase in annual precipitation of 0.5–1.0 % per decade in the 20th century over large parts of the higher northern latitudes. Studies of Norwegian precipitation series indicate an increase in annual and partly in seasonal precipitation also in Norway (Hanssen-Bauer 2005; Hanssen-Bauer and Førland, 1998). Hanssen-Bauer (2005) found that the annual precipitation had increased between 0.3 % and 2.1 % per decade for various parts of Norway during the period 1895–2004. The largest increase (1.5–2.0 % per decade) has occurred in Western-Norway and large parts of Central and Northern Norway. In most regions the increase is largest during spring and winter. Figure 2.1 shows area-weighted variations in annual precipitation for the Norwegian mainland since 1900. The figure indicates that annual precipitation has increased substantially since ca. 1970, and this is particularly valid for the winter season.

The IPCC-TAR report (Folland et al., 2001) concluded that over the latter half of the 20th century it is likely that there has been a 2 to 4 % increase in the frequency of heavy precipitation events reported by the available observing stations in the mid- and high-latitudes of the Northern Hemisphere. In a study of trends in maximum 1-day precipitation in the Nordic region, Førland et al. (1998) found a maximum in the 1930s and a tendency of increasing maximum values during the 1980s and 1990s.

The capacities of existing Norwegian dam constructions and river regulations are dimensioned and evaluated against estimates of extreme floods and precipitation based on long series of observations. A key issue is whether these estimates are still valid, or whether the climate development during the recent global warming urges a revision of the present return period values. Alfnes & Førland (2006) studied whether the maximum 1-day precipitation in Norway has changed during the last century and if the design values, used in dam constructions, river regulations, and urban runoff systems etc. would be different if calculated on the last 30 years of observations compared to those of the standard normal period, 1961–1990.

In Norway extreme precipitation values with

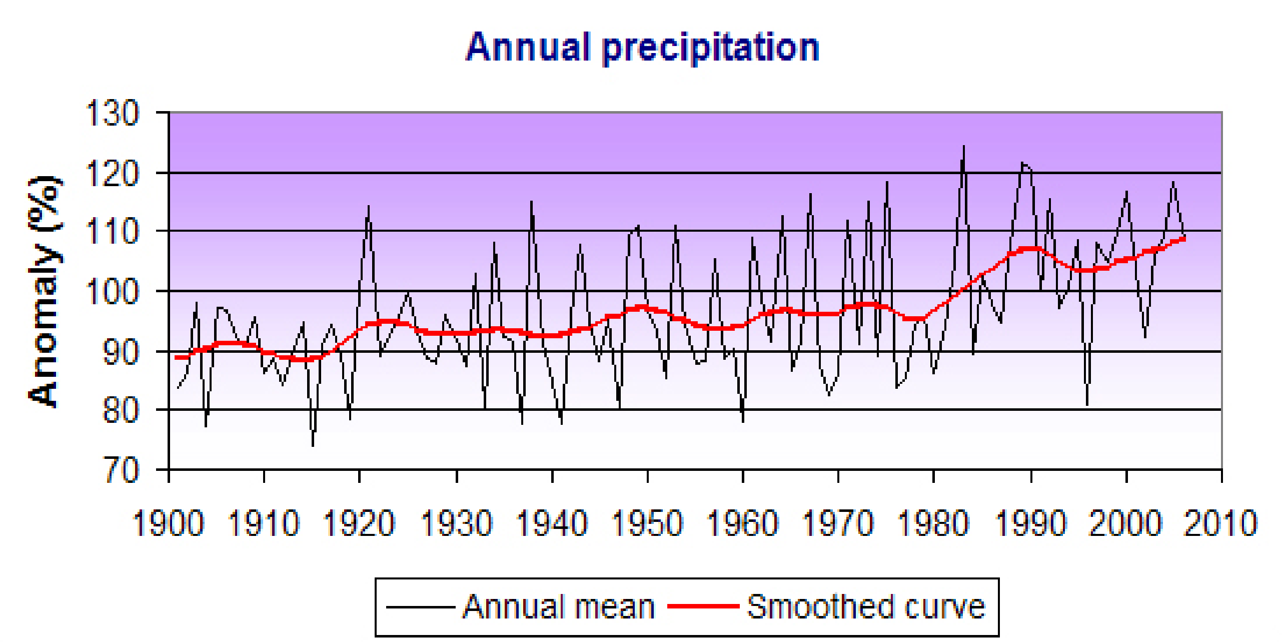


Figure 2.1 Annual precipitation for the Norwegian mainland, 1900-2006. Anomalies are ratios (in percent) to the 1961-1990 averages («normals»). The smoothed curve indicates decadal variability, while the thin line represents values for single years. The last 3–4 values on the smoothed curve are indicating preliminary results as they may be changed when more recent years are added.

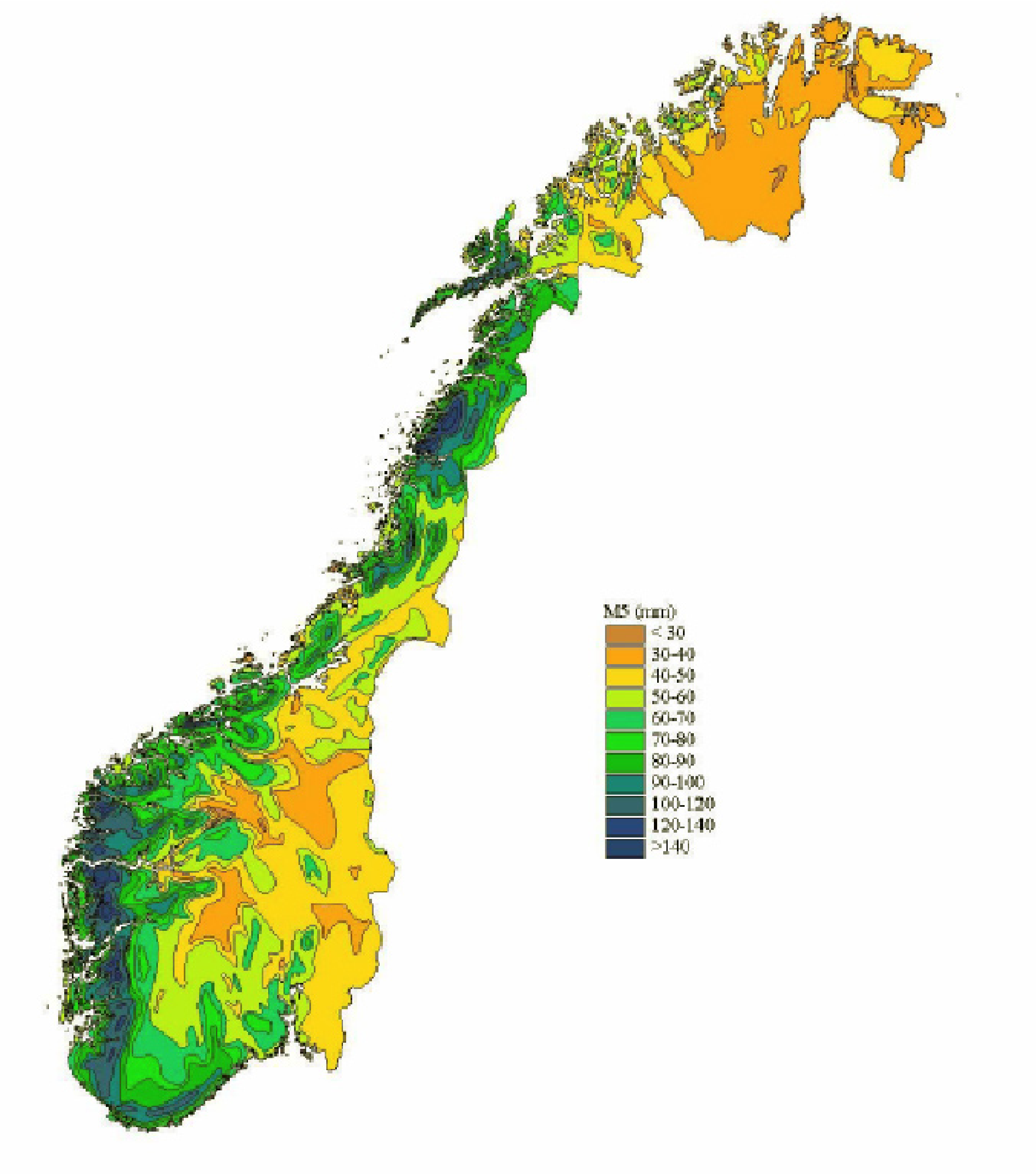


Figure 2.2 a *Estimated 1-day extreme precipitation with a return period of 5 years (M5(24h)) for the normal period 1961–90.*

long return periods are estimated by a modified version (Førland, 1992) of the British M5-method. The basic value for the estimations in Norway is the 24h precipitation with a return period of 5 years, M5 (24h). In a Nordic comparison (Alexandersson et al., 2001) it was found that the General Extreme Value (GEV) and M5-methods gave reasonable estimates also for the most extreme values.

Large local and regional gradients exist for maximum 1-day precipitation as well as annual precipitation in Norway. This is reflected in the M5 (24h) values which for the 1961–90 normal period range from ca. 30 mm in interior parts of southern Norway and Finnmarksvidda, to more than 140 mm in rainy parts of western Norway and in Nordland county (Figure 2.2a).

Based on a large number of stations (>200) an investigation was made into whether there were any changes in design values for extreme 1-day precipitation from the normal period 1961–90 to the

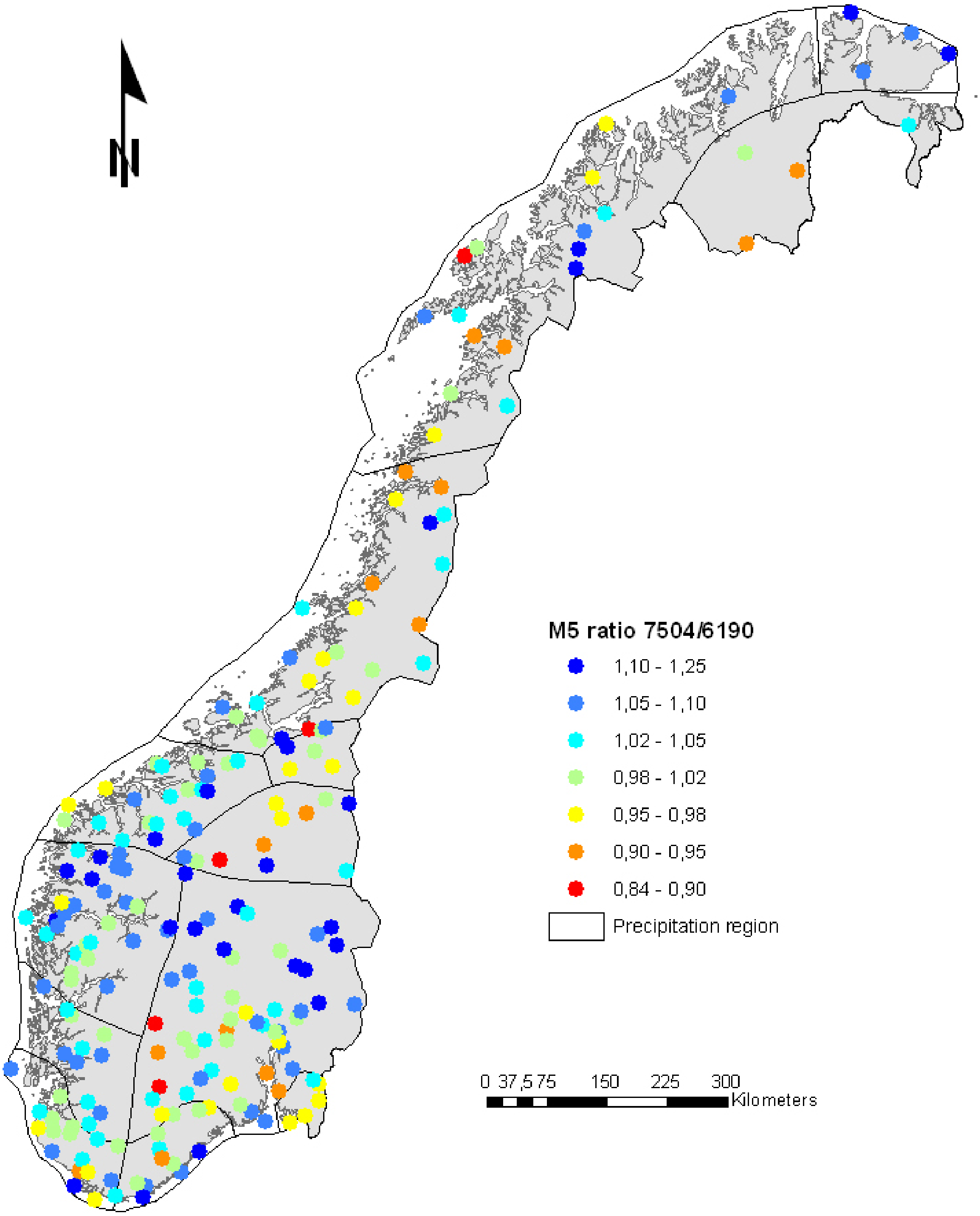


Figure 2.2 b *Relative changes in M5(24h) from 1961–1990 to 1975–2004.*

period 1975–2004 (Alfnes & Førland, 2006). For more than half of the stations the changes were less than ± 5 %, but Figure 2.2b reveals large gradients even between neighbouring stations. By analysing median values for groups of stations, it was found a general increase of up to 5 % in the regions Western Norway and Møre & Romsdal. In south-eastern Norway («Østlandet») there was a small increase in M5 (24h)-values in northern parts, whereas the changes were more randomly distributed in the rest of this region. For the rest of the country there were no distinct regional patterns.

For 33 stations with series back to 1900 the long-term variability was studied by analysing the 30-years moving averages of M5 (24h) during the whole period (Alfnes & Førland, 2006). At some stations the M5 value for the most recent 30-years period is close to maximum in the studied period and for other stations

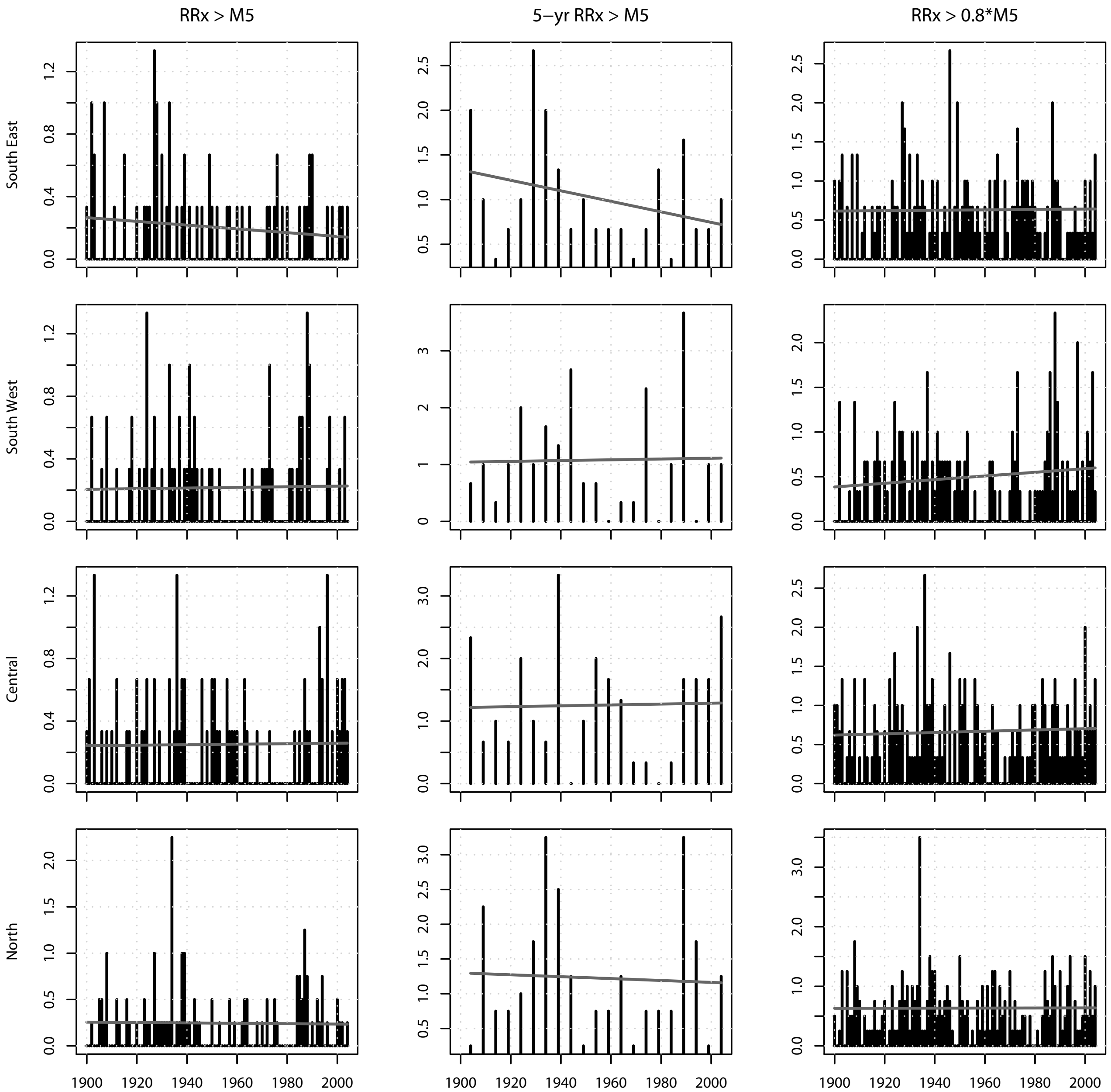


Figure 2.3 *Extreme 1-day precipitation events per station for different Norwegian regions. Column 1: Annual number of events ≥ M5 (1-day), Column 2: as column 1, but accumulated over five years, Column 3: Annual number of events ≥ 0.8*M5(1-day).*

approximately at minimum. A local maximum in the periods ending around 1940–1960 and a tendency of increasing M5 values during the latest 10–15 years is seen for many of the stations. Large fluctuations in the M5 value were also observed at stations where no significant long term trend is found in the maximum precipitation.

Trend analyses of the maximum 1-day precipitation indicate an increase since 1900 for two thirds of the stations. The change is moderate for most of the stations and the trend is significant at 5 % level at only 4 of the 33 stations studied. The largest increase in the maximum precipitation is found in the south-western part of Norway. However, stations with no trend or negative trend, although insignificant, are also present in this area.

High frequencies of extreme precipitations events (precipitation greater than the M5 (24h)) were found in the 1920s–1930s and in the south western and central regions in the 1980s–1990s (Figure 2.3 column 1). A clear decrease in the occurrence of extreme rainfall events during the last century was found in the south eastern regions. In the other regions the changes were minor.

The change in frequencies becomes more visible when accumulated over successive discrete non-overlapping five years periods (Figure 2.3, column 2). Weak tendencies of decreasing frequencies are seen in the south western and northern regions whereas a weak increase is seen in the central regions. The picture changes when the threshold is decreased to 80 % of the M5 (1-day) value. Then a general increase in the frequencies is seen in all regions (Figure 2.3, column 3), although rather weak except for the south western regions. This indicates that the frequency of «extreme extremes» has decreased but that there is a general tendency of increased frequencies of large 1-day precipitation values.

2.2 Projected changes in extreme precipitation

2.2.1 Downscaled scenarios for seasonal, annual and extreme precipitation up to year 2050

(Eirik J. Førland, Torill Engen-Skaugen and Inger Hanssen-Bauer, met.no)

Empirically downscaled scenarios based upon the Max-Planck-Institute's GSDIO integration with the ECHAM4/OPYC3 global climate model following the IPCC IS92a emission scenario give an increase in the average annual precipitation of 0.3 to 2.7 % per decade up to year 2050 all over Norway (Hanssen-Bauer et al. 2001). The projected increase rates are generally smallest in south-eastern Norway, where they are not statistically significant (at the 5 % level) and largest along the north-western and western coast where they are highly significant. In winter, statistically significant positive trends (+1.8 to 3.2 % per decade) are found all over the country. The largest increase rates are found in southern Norway. Also in autumn, the precipitation increase (+0.6 to 5.9 % per decade) is statistically significant at most places. The largest autumn increase rates are found in western and north-western regions. Modelled spring precipitation

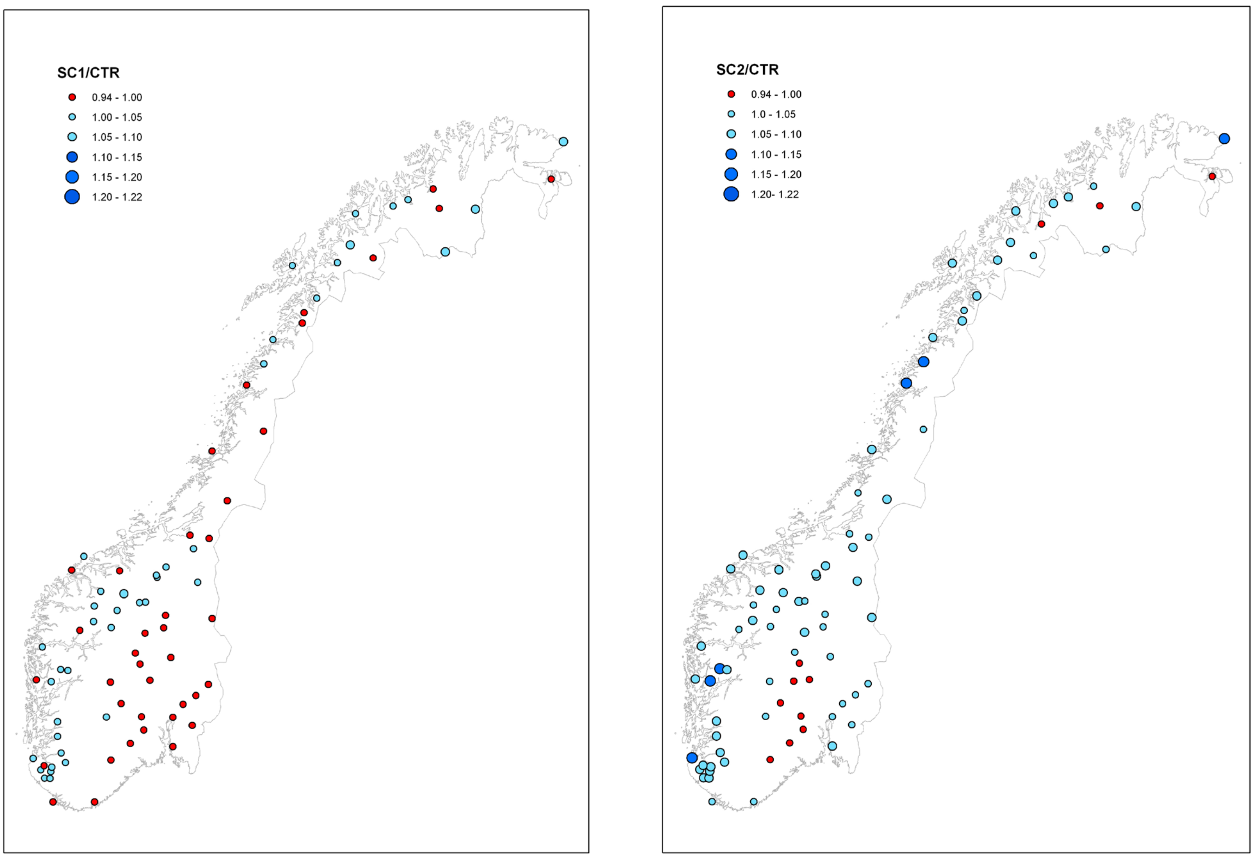
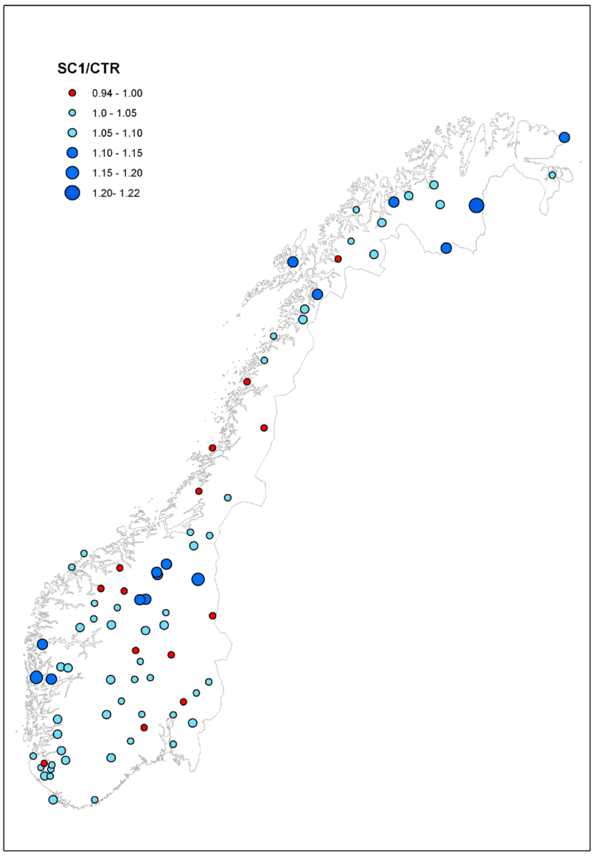


Figure 2.4 *Ratios between 95 percentile 1-day precipitation values during a) 2000–2024 (SC1) and b) 2025–2049 (SC2) vs. control run for the period 1980–1999. Based on scenario from ECHAM4/OPYC3 following IS92a.*



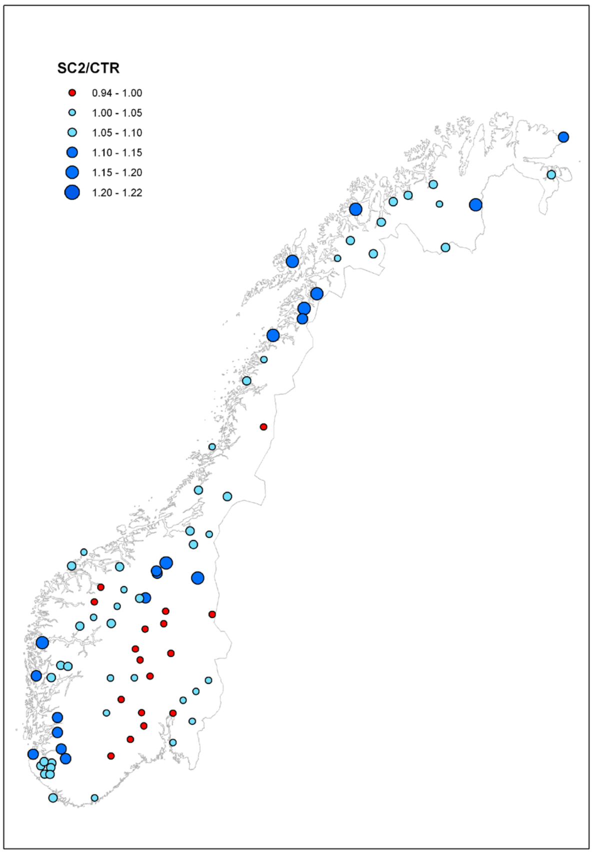
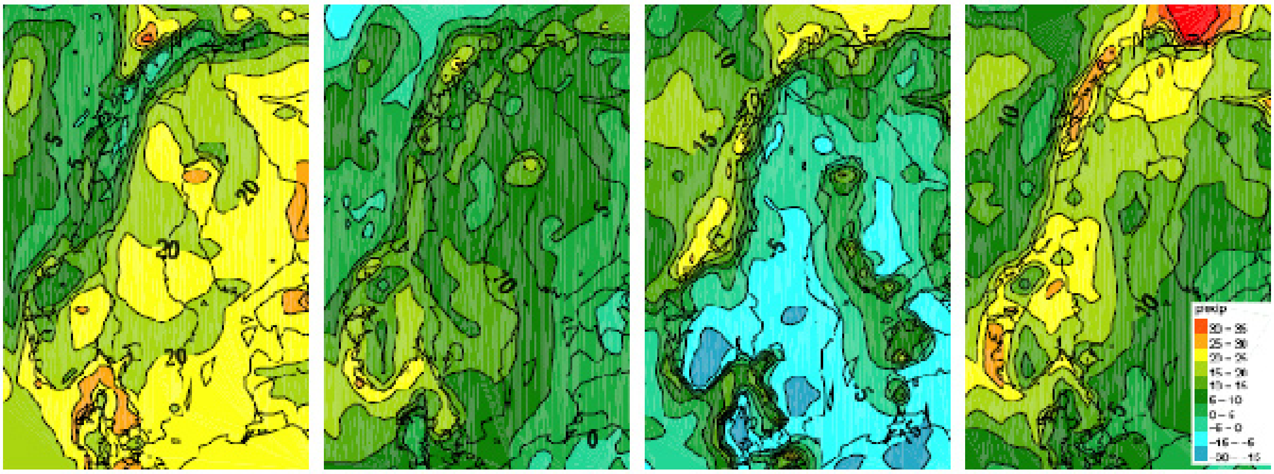


Figure 2.5 Same as Figure 2.4, but for the 99 percentile.

tends to decrease in southern Norway and increase in northern Norway. These changes are statistically significant only in two northern regions. Modelled summer precipitation tends to decrease in eastern areas and increase in western areas, but the changes are statistically significant in just 6 of 13 regions. The results from the empirical downscaling mainly agree with the precipitation scenarios that were calculated by dynamical downscaling from the same global scenario. An exception is found during summer, when dynamical downscaling tends to project significant precipitation increase in larger areas.

A method for adjusting dynamically downscaled daily precipitation values to be representing specific sites has been developed by Engen-Skaugen (2004). The method reproduces mean monthly values and standard deviations based on daily observations. The trend obtained for precipitation in the regional climate model is maintained, and the frequency of modelled and observed number of rainy days shows good agreement. This method is applied to dynamically downscaled precipitation scenarios based on MPI GSDIO integration (IS92a emission scenario) for a large number of precipitation stations in Norway for a control period (1980–99), and a scenario period 2000–2050.

Figures 2.4 and 2.5 show one scenario for projected changes in the 95 resp. 99 percentiles of daily precipitation and indicate a weak increase in extreme daily precipitation up to 2025, but a stronger increase during 2025–2050. The strongest increase is found in Western Norway and coastal regions in Northern Norway. For several stations in South-eastern Norway the figures indicate reduced extreme daily rainfalls for both scenario periods.



Winter Spring Summer Autumn

Figure 2.6 *Combined projections of changes in percent (from 1961–90 to 2071–2100) in seasonal precipitation from dynamically downscaled scenarios from two global climate models (MPI and HAD) based on B2 emission scenario.*

2.2.2 Projected scenarios for changes in total and extreme precipitation up to year 2100

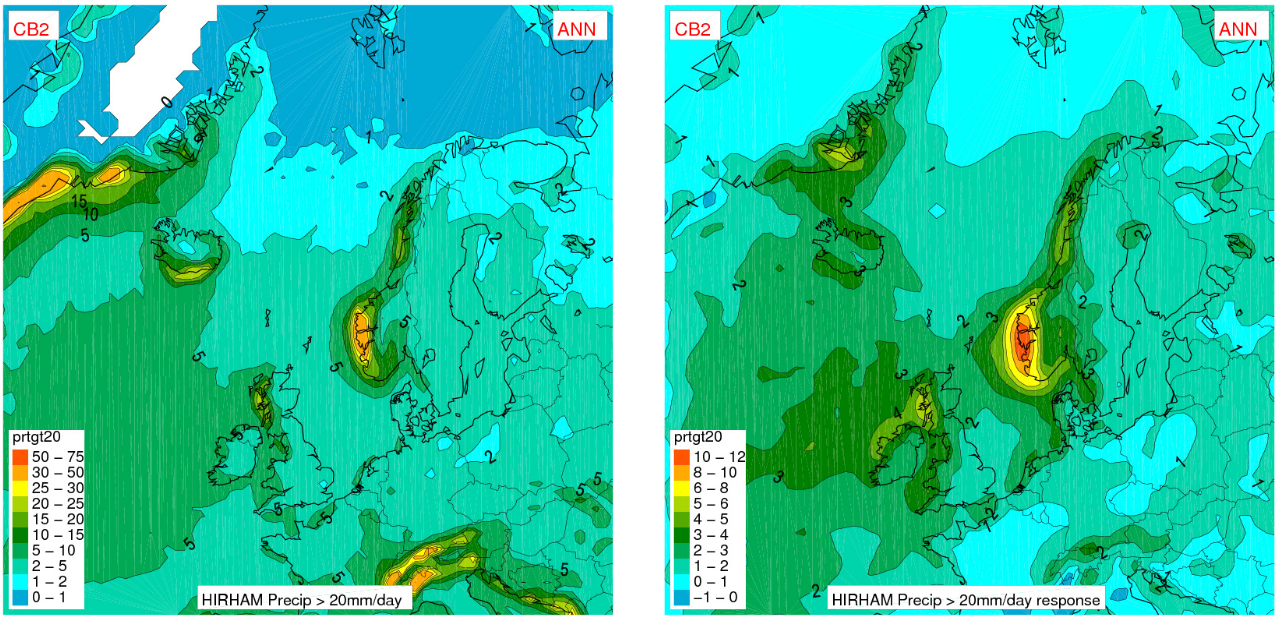
(Eirik J. Førland and Jan Erik Haugen, met.no)

To reduce uncertainties in the scenarios for Norway, dynamically downscaled results from two global climate models giving quite different precipitation projection are combined (see *http://regclim.met.no*). The models used are the British UK Met Office Hadley-Centre HadCM3 model (HAD) and the German Max-Planck-Institute's ECHAM4/OPYC3 (MPI) model, where both simulations have followed the IPCC SRES B2 emission scenario.

The results in Figure 2.6 and Table 2.1 display changes over 110 years from the period 1961–1990 to the period 2071–2100. The projections indicate that the annual precipitation will increase by 5 to 20 % in different regions in Norway. The increase is largest along the south-western coast and far north. The largest seasonal changes are found for the autumn; where the increase in Western, Central and Northern Norway is larger than 20 %. In South-eastern Norway the precipitation during autumn and winter is projected to increase by 15–20 %, while the summer precipitation in parts of this region may be reduced by up to 15 %.

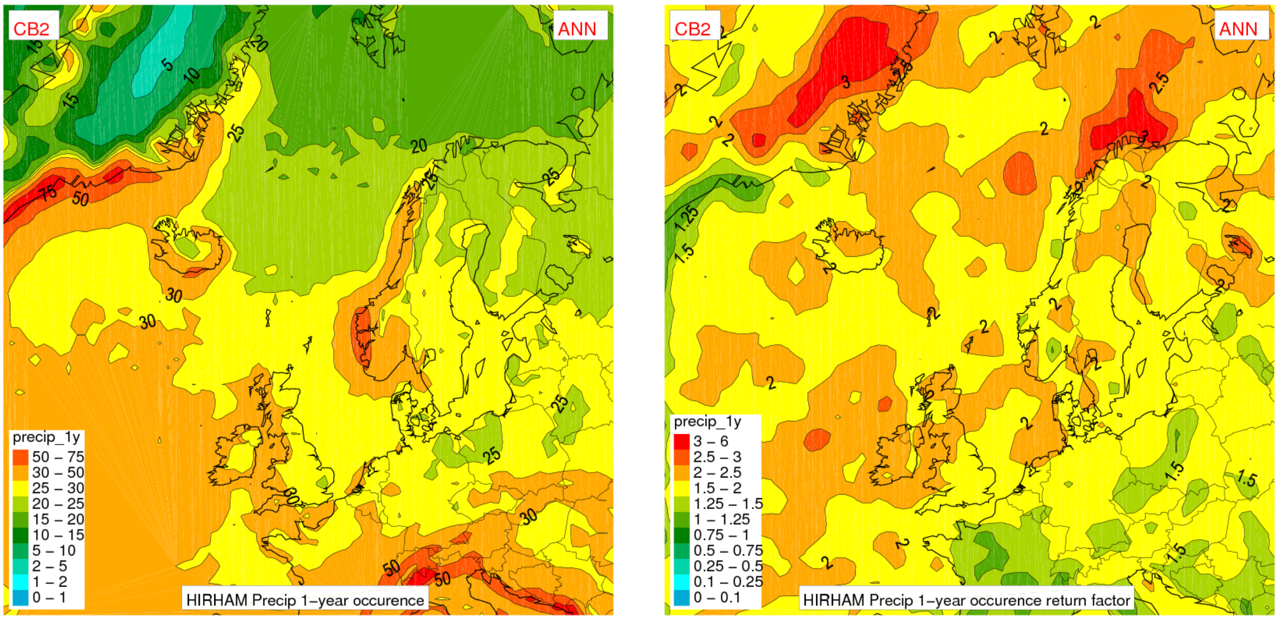
Table 2.1 *Average change in precipitation (%) from the period 1961–1990 to 2071–2100. Results are based on dynamically downscaled scenarios from two global climate models (MPI and HAD, B2 emission scenario).*

	Annual	Spring	Summer	Autumn	Winter
Total (Norwegian mainland)	13	13	3	20	13
Finnmark & Northern Troms	14	11	12	23	7
Nordland & South Troms	12	10	13	18	6
Western Norway (incl. Trøndelag)	13	14	2	20	14
Southeastern Norway	12	15	–5	19	18



a) ***b)***

Figure 2.7. *Number of days per year with rainfall > 20 mm/day.*
a) Simulation for the period 1961–90.
b) Projected changes up to the period 2071–2100 from a combination of the HAD and MPI scenarios following IPCC SRES B2 emission scenario.



a) ***b)***

Figure 2.8 a *Smoothed map of average annual maximum daily precipitation (mm/day) during 1961–1990.*
Figure 2.8 b *Number of times per year the rainfall amounts in Figure 2.8 a will occur during 2071–2100. Numbers larger than 1 indicate that the present extremes will be more common in the future.*

The combined downscaled results are also used to study changes in extreme precipitation (http://regclim.met.no). Figure 2.7b indicates that there will be an increase of 15 days per year with precipitation exceeding 20 mm/day in parts of Western-Norway. This is an increase in number of days with more than 20 % (cf. Figure 2.7a). In the other parts of Norway the absolute change in number of days > 20 mm will be substantially lower.

For all of Norway daily rainfalls that are considered extreme today (Figure 2.8a) will be more common in the future according to these scenarios (Figure 2.8b). Along the coast of Troms and Finnmark daily rainfall values similar to today's annual maximum daily values will occur 2–3 times per year.

2.2.3 Novel analyses of empirically downscaled precipitation scenarios

(Rasmus Benestad, met.no)

The description of precipitation is still crude and based on bulk parameterization of sub-grid processes, and the GCMs do not yet give accurate description of details associated with small-scale phenomena such as fronts and cyclones (gales/storms), Figure 2.9–2.10. Since storms are not well-represented by the GCMs, precipitation associated with these low-pressure systems will be uncertain. In order to give more accurate description of these phenomena, RCMs with higher spatial resolution can be utilized, typically 50x50 km^2. However, even RCMs may not capture all intense local downpour (Figure 2.9–2.10), but nevertheless give useful information about the large-scale precipitation patterns. The GCMs are able to provide a crude of how precipitation may change with time, even though they are limited to lager-scales. Model simulations from the RegClim project for the future point to increases in extreme precipitation (definition: more days with high precipitation amounts and higher amounts than today).

Regarding 24h extreme precipitation, some simulations (Figure 2.11) point to an increase in the frequency of cases when the amounts exceed today's 95-percentile. These estimates are based on IPCC (2007), and utilize geographical information to generate maps with high spatial resolution (5'x5'). These scenarios indicate that there may be more extreme precipitation in the future. Scenarios derived using empirical and statistical analysis indicate a moderate increase (up to 30 percent) in the probability for exceeding present-day 95-percentile. Analysis of historical trends in extremes also indicates some increase in extreme precipitation, but these trends have some uncertainties. Nevertheless, the scenarios seem to provide a similar picture as the past trends in terms of an increasing trend. However, different approaches in the spatial analysis give different results for the high-altitude mountainous regions, where one choice yields no correlation between altitude and extreme precipitation whereas another suggests a reduction in the high-

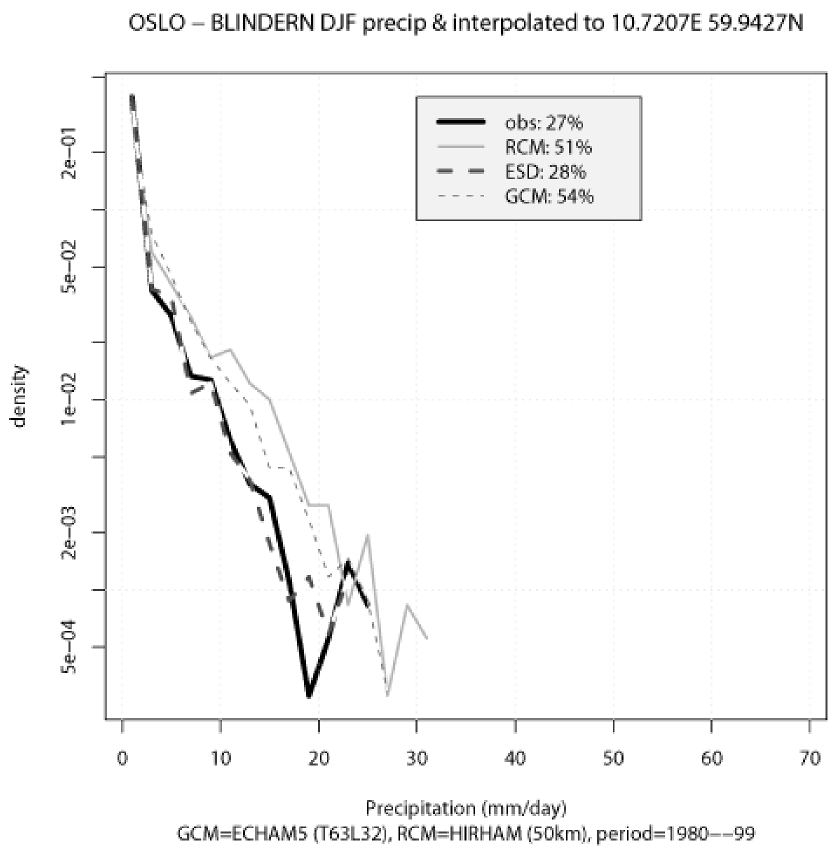


Figure 2.9 *An example illustrating the limitation of GCMs and RCMs in representing the local precipitation statistics. The percentages given in the legend indicate the fraction of wet days.*

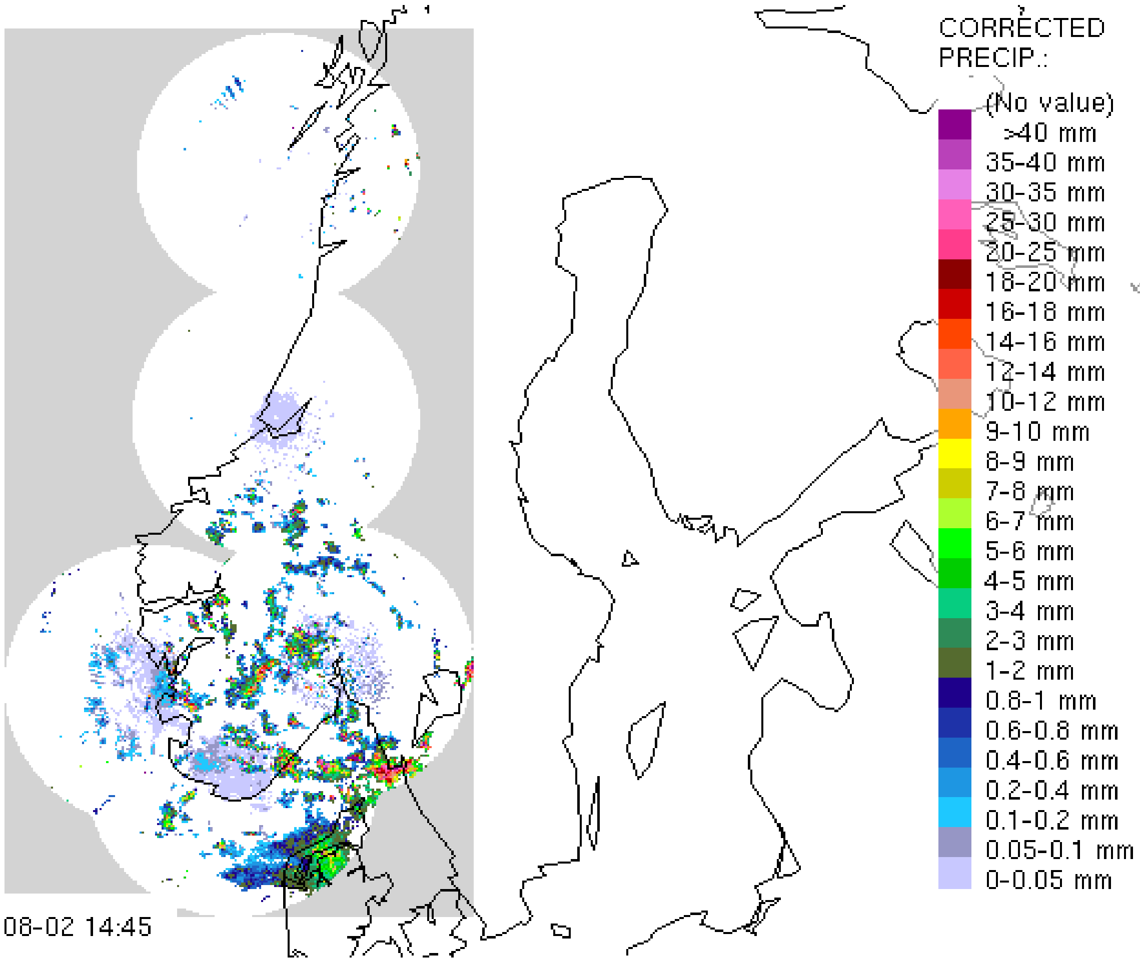
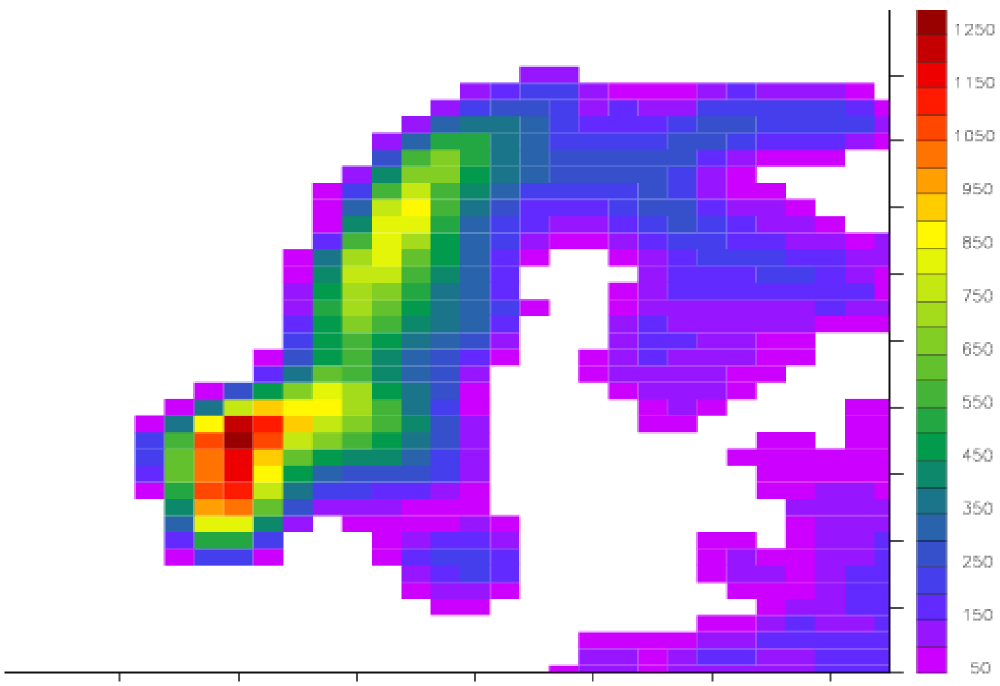
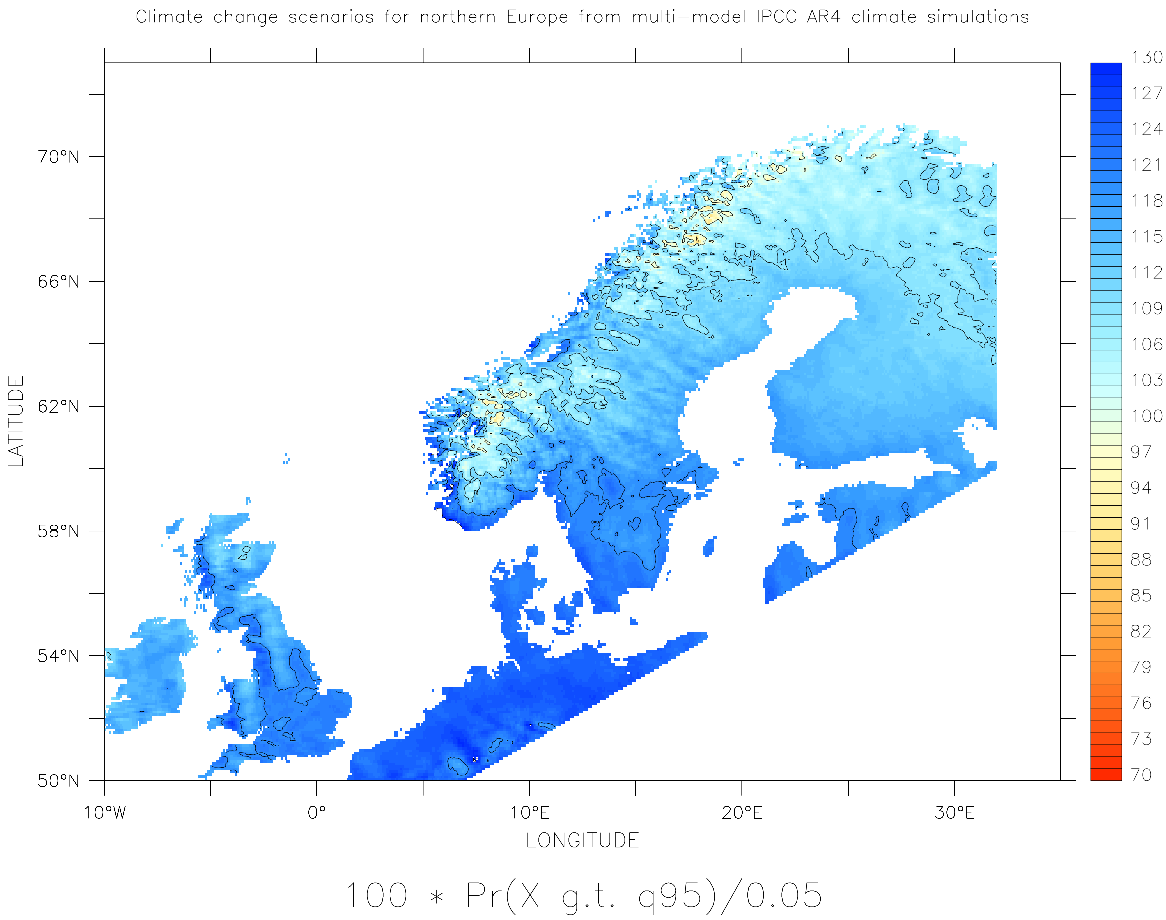


Figure 2.10 *Example showing precipitation on fine spatial scales (above) from radar reflectivities that RCMs are unable to capture because their typical spatial resolution is too low. Panel below shows the RCM topography, simultaneously providing picture of its spatial resolution.*





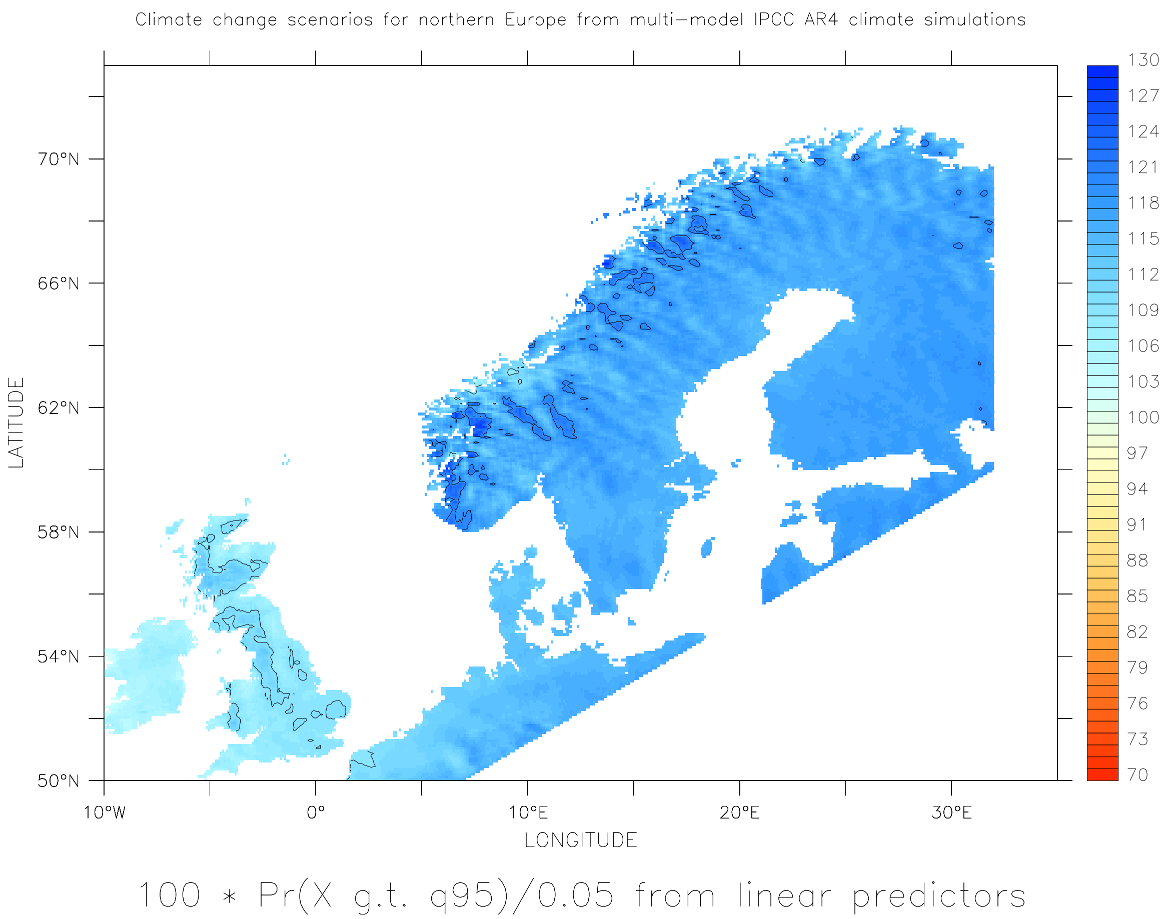


Figure 2.11 *Changes in probability of any day having precipitation exceeding the present-day 95-percentile, expressed in % as the ratio Pr(year 2050)/Pr(present-day).*

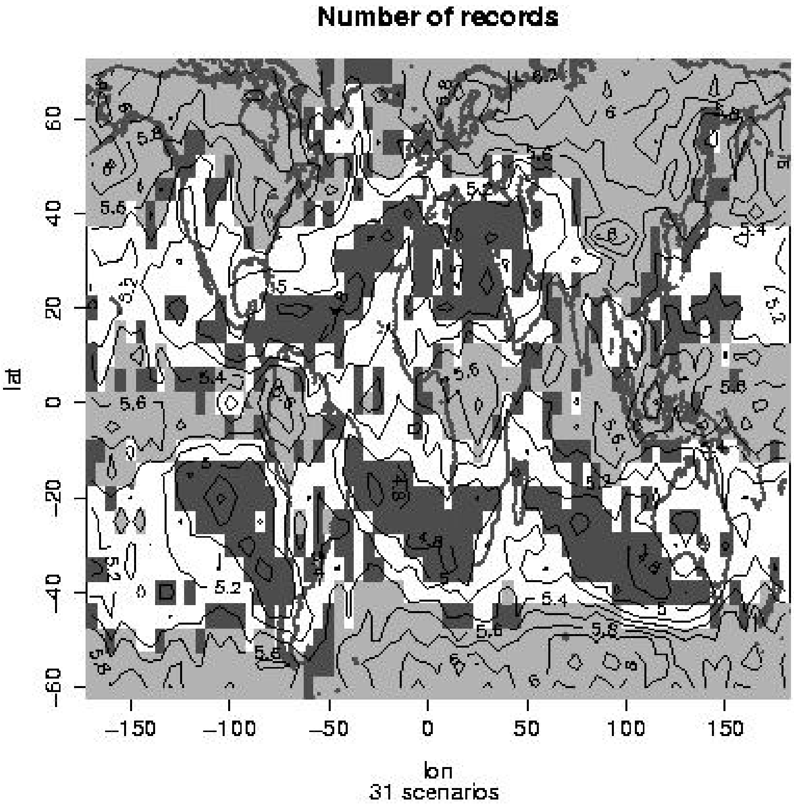


Figure 2.12 *Maps showing the estimated number of record-breaking events for monthly precipitation for 2000–2099. Light grey shading show regions with anomalously high recurrence of record-events, implying more wet conditions in the future. Dark grey marks regions with low number of record-breaking events, typical for regions which are becoming drier.*

altitude precipitation extremes. Palmer & Räisänen (2002) analysed several GCMs and concluded that the probability for the future winter precipitation in northern Europe exceeding two present-day standard deviations above the present-day normal may increase by ~500 %. The GCMs in general indicate that the climates of the higher latitudes will get wetter whereas the sub-tropics will on average receive less precipitation (Figure 2.12). An analysis of the return interval of extreme monthly precipitation amounts for a selection of sites in Norway point to some increase, but not everywhere.

Extreme climatic episodes may include persistent droughts or extremely wet seasons, such as the autumn 2000 in south-eastern Norway. The forest fire risk is correlated with droughts. Furthermore, some studies suggest that the variability may increase with more pronounced inter-annual changes, with more droughts and heat waves as well wet seasons and flooding. Heat waves in Europe have been linked with persistent high pressure systems («blocking»), and dry soil does not moderate the surface temperature in the same way as wet soil, due to the absence of evaporation. High temperatures moreover increase the evaporation. Even though the precipitation is projected to increase in Norway on average, changes in the inter-annual variations may lead to more droughts and thus the length and severity of the droughts may be more important for the forest fire risk than the average rainfall. Furthermore, the GCMs give different indications for the different seasons: during winter there are more pronounced positive precipitation trends whereas the indications for the summer are more mixed. If the future turns out to become more persistent in terms of wet and dry spells, for instance as a consequence of longer duration with the winds blowing from the same direction, then this may have implications for the geographical rainfall patterns (there is little rainfall along the west coast when the winds blow from east, but more rain when the winds are from west). Another aspect is the position of the storm track, and the question whether we can expect a systematic shift in its position. The GCMs indicate that a global warming may result in a poleward shift of the storm tracks. The implications are that precipitation associated with cyclones will increase in areas where there the storm frequency increases (for instance northern Norway) whereas in regions where the low pressure systems become less frequent may experience a reduction in the precipitation associated with low-pressure systems. Even though the summer time rain often is caused by convective processes (warm air rises locally and create cumulonimbus clouds that are typical for the warm afternoons), precipitation requires that the air contains sufficient moisture (water vapour). The main source for moisture is the oceans, but lakes and evaporation from the ground may also act as sources. Storms and winds play an important role in transporting and redistributing the atmospheric moisture.

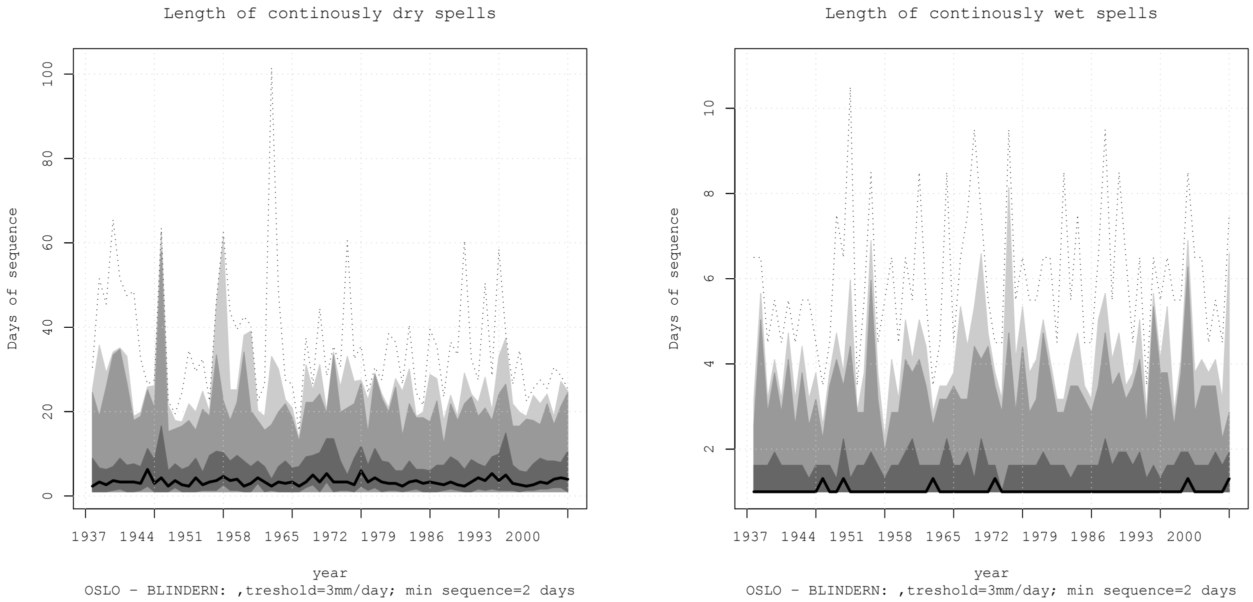


Figure 2.13 *Analysis of length of dry intervals (left) and the length of wet spells (right) for historical precipitation measurements at Oslo Blindern. The grey shadings indicate 2.5–97.5 percentile interval (dark), 5–95% interval, and 25–75% (light). Black line marks the median, and thin dotted line the annual maximum length.*

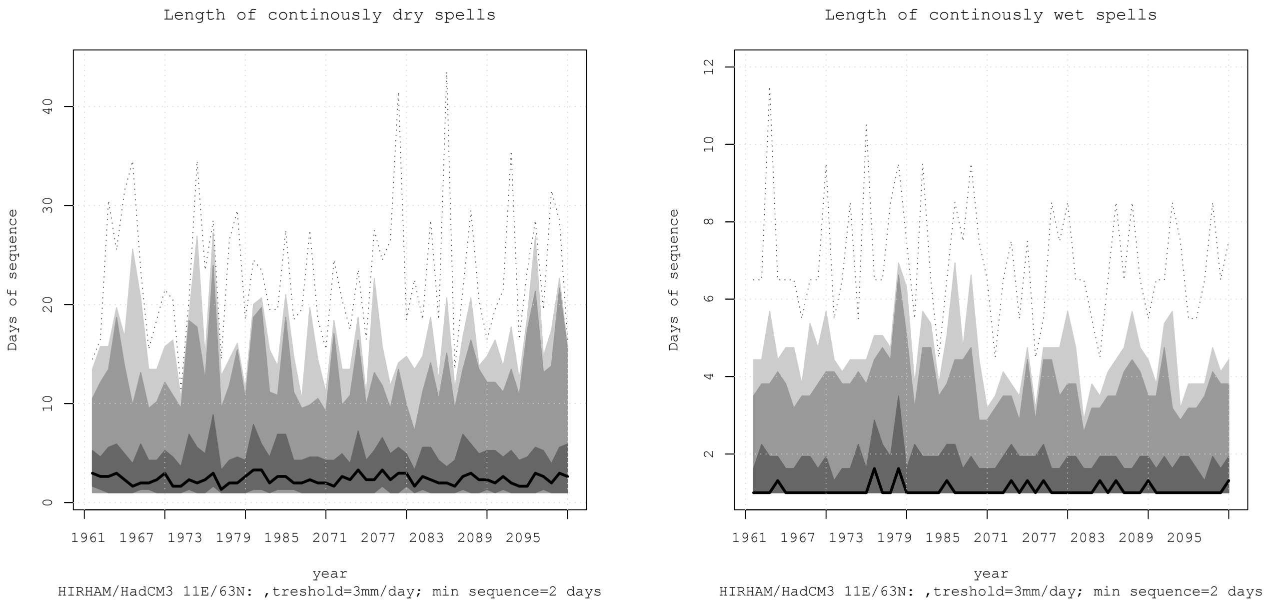


Figure 2.14 *Same as Figure 2.13, but for RCM results (HIRHAM/HadCM3 A2).*

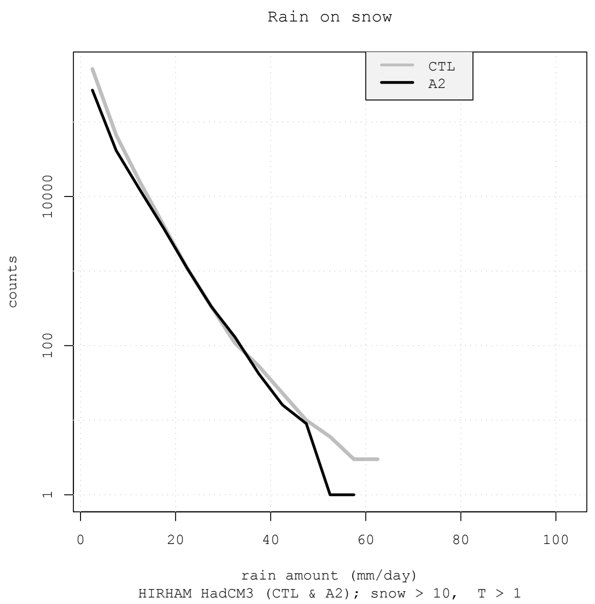
Analysis of the length of wet and dry spells suggests that in the past there generally have been longer periods with rainfall than with no rain. But there is no clear trend in the duration of the wet or dry spells, neither in the historical records nor in the projected scenarios. Figure 2.13 shows an analysis of the lengths of wet and dry spells based on 24-h precipitation data, and the most pronounced character is the decadal variations. Figure 2.14 shows results for a similar analysis based on RCM simulations for a control period and projections for the future.

Record-event analysis, examining the recurrence of record-breaking events, indicates that for monthly precipitation, one can expect more records (i.e. an increase) especially during winter, spring and autumn. The record-event analysis for monthly 24-h maximum precipitation, on the other hand, does not give any unanimous trend (statistically significant at the 5 % level) that the records have become unusually frequent in the Nordic countries.

2.2.4 Rain on snow

(Rasmus Benestad, met.no)

Analysis of changes in the combination of heavy rain and snow melt (Figure 2.15) is based on simulations with RCMs from the PRUDENCE project (*http://prudence.dmi.dk*). The control period for this analysis was 1961–1990, and the scenarios were based on the SRES A2 for the period 2071–2100. The analysis, based on only one climate simulation, suggested a reduction in the number of events with heavy rain coinciding with strong melt-off. Spring flooding can easily arise from a combination of heavy rainfall and rapid melting. Benestad & Haugen (2006) carried out a more advanced analysis for such complex extremes (bivariate or multivariate distributions) as a combination of high spring-time temperature and high rainfall amounts, based on RegClim (*http://regclim.met.no*) results and the HIRHAM/ECHAM4 RCM. An increase in the frequency of combined high temperature and heavy precipitation was inferred for the spring season, but this analysis did not account for changes in the snow depth and cover. It was also noted that the RCM had a limited accuracy due to its spatial resolution.



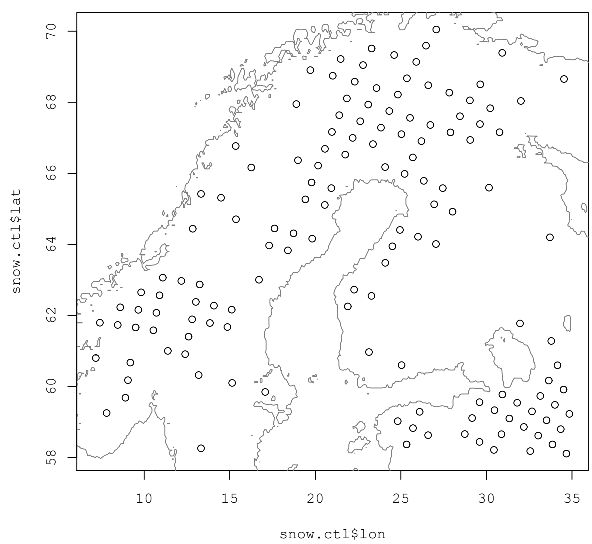


Figure 2.15 *Left: Distributions representing the frequency of precipitation (amount given along the x-axis) coinciding with a temperature greater than 10 °C and at least 10 mm equivalent snow on the ground. The y-axis has a logarithmic scale.*
Right: Map showing locations of data from which the curve was based.

3 Expected change in the occurrence of floods as a consequence of climate change

(Lars Roald, NVE)

Key points

- Floods are caused by snowmelt and/or rainfall. Changes in the land use and impoundment of water in reservoirs will change the flood regime.
- The largest floods in Norway have occurred at the start or the end of a sequence of very cold years during the Little Ice Age. The generation of intensive rainfall during these events was nevertheless linked to high temperatures.
- Rainfall floods tend to occur in warm periods e.g. the 1930s and since 1987.
- Moderate winter floods will be more common in a warmer climate. The potential for large snowmelt floods will decrease in the later part of the scenario period.
- The snow storage can increase in the mountains, at least early in the period because of increasing winter precipitation. Large snowmelt floods can therefore still occur until the warming is high enough to cause melting episodes, even in high lying basins.
- Local flash floods can become more common in a warmer climate. These floods can cause local damage and loss of lives in inland valleys, especially where step tributaries join the main river on the valley floor.
- Late autumn floods will be more common, especially in basins in west Norway.
- Glacier melting can cause more floods resulting from drainage of glacier dammed lakes.
- The vulnerability to flood damage will increase more than the actual flood risk because of more intensive developments on the flood plain.

3.1 Natural variability of floods

3.1.1 Flood causes

Floods are caused by snowmelt and/or rainfall. Most large basins cover a fairly large elevation band. Major rivers especially in the East can suffer up to three floods in the spring season, a early lowland flood because of mild spells in the winter or early spring, a secondary flood caused primarily by melting in the upland areas and a third event caused by melting in the alpine part of the basin. This is typical for rivers like River Glomma. Large snowmelt flood occurs usually when two or three of these floods coincide. Melting tends to occur more concentrated in mountain areas without large differences in altitude, e.g. at the Hardangervidda plateau in the South and Finnmarksvidda in the North.

The magnitude of a flood is strongly dependent on the initial conditions. A large snow cover may cause severe flooding, but only in combination with quite a few days of high temperatures and preferably some rainfall. Large spring floods occur rarely without rainfall at all except at Finnmarksvidda. The conditions of the ground can also increase or reduce the magnitude of a flood. A flood can be reduced if the soil moisture storage and ground water level is low, while saturated ground will result in more runoff at or near the surface. Local flooding is also a problem if the ground is frozen during winter rainfall, a phenomena well known along the west coast to Lofoten.

Rainfall floods are either caused by long duration rainfall or locally intensive thunderstorms. Long duration rainfall is linked to dominant weather types and will affect large regions, while rainstorms usually affects small areas, but has the potential of causing severe local damage and loss of lives.

Floods can also be caused by damming of rivers because of ice, with subsequent ice runs as the ice dam breaks. Changes in climate can have strong influence on ice conditions and on the occurrence of ice dams and ice runs. This is discussed in Chapter 4.

Some floods are caused by damming of rivers by avalanches, landslides or rock-fall, but the primary cause of these events is often heavy rainfall and flooding prior to the slide. The clay-slide into River Vorma in 1795 dammed the river for 111 days, resulting in a rise of the upstream level of 6 m before a channel was opened by the Army. Glaciers can cause flooding because of heavy glacier melting or by release of water from glacier dammed lakes (*jökullhlaup*). Some rivers near glaciers have been known to pulsate because of temporary damming by terminal moraines. The best known cases are River Mjølkedalselva upstream Lake Bygdin, River Leira in Bøverdalen and River Vulu in Ottadalen.

Large floods generally occur when several of the conditions mentioned above are present. The precipitation records back to 1895 include many events of 100 mm or more in a day, especially on the western side of the main mountain ranges, but only a minority of these events results in severe floods, because of the initial conditions of the basin or because the precipitation may have fallen as snow in parts of the upstream basin.

3.1.2 Changes in the occurrence of floods over time

Information of early floods can only be obtained using paleoflood methods, see for example Nesje et al. (2001). Some information of flood disasters in Norway can however be found back to the 1340s in a few documentary sources. Documentation from England, Germany, Austria and Switzerland (Lamb, 1982; Pfister, 1999) indicate that this period was rich in floods also in West and Central Europe. Information of other floods in Norway in the 15th and 16th century is anecdotal, but from the second part of the 17th century documentary information is available because of the damage reports which formed basis for tax deductions (Riksen, 1969). The 17th and 18th century had the most severe spells of cold weather during the little ice age, and some very large floods occurred, especially in the 18th century, which by far exceed the magnitude of later floods. Macklin et al. (2005) have noted that large floods tend to occur at the start or end of especially cold periods, and this is also the case in Norway. One of the coldest spell of the little ice age was 1695–97, and from 1689 to 1692 several large floods caused substantial damage at Vestlandet and Trøndelag. The 1650s were also very cold, and the early 1660s were also rich in floods. The large flood of 1743 and a slightly smaller 1745 in West Norway occurred at the end of another cold spell, and cold spell between 1773 and 1789 was both initiated by a large flood in 1773 and ended with Storofsen in July 1789. A large flood occurred in Vosso in 1790 and a disastrous one in Skienselv in 1792. These events seem to occur when the dominant circulation pattern is shifting. One common factor in many of the events is fairly high temperatures and intensive rainfall. The winter 1789/90 was extremely mild, it has been recorded that it was almost impossible to remove the damaged timber from the forests in East Norway because of lack of snow and unfrozen lakes, streams and bogs. Some of these events such as Storofsen were caused by rather unusual weather patterns as documented by Østmo (1985) based on the Kington (1988) reconstruction of daily weather maps for the 1780s. The weather pattern causing Storofsen is also known to have caused some large flood disasters in Central Europe, most recently in August 2002. If this weather pattern should appear more frequently, it is likely that more of this type of floods would appear.

Figure 3.1 show the number of known floods from the 1340s to 2005 based on more than 700 flood events so far identified. The floods have subjectively been classified according to their severity, see Appendix 1. The early floods were all severe, as smaller floods would not have been recorded. Information about later floods is later mostly based on direct observations of precipitation and stage/discharge. The classification of floods in regulated rivers has been based on naturalised flow data to obtain comparable statistics. The graph shows high frequencies from 1920 to 1940 and from 1985 to 2005. Most of the floods between 1940 and 1985 were not severe.

Floods and droughts tend to cluster in flood-rich periods, with longer flood-poor periods in between, also called the Joseph Effect (Mandelbrot & Matalas, 1968). This is probably linked to spells of the dominant atmospheric circulation. Roald (1999) examined many long term series in Norway and were unable to find significant trends in the annual flood of most of the series unless the series had been regulated. This is also the case for Sweden, Lindström & Bergström (2004). Changes in the runoff regime including floods and droughts based on 150 Nordic runoff series have recently been examined for the Nordic countries (Hisdal et al. 2006).

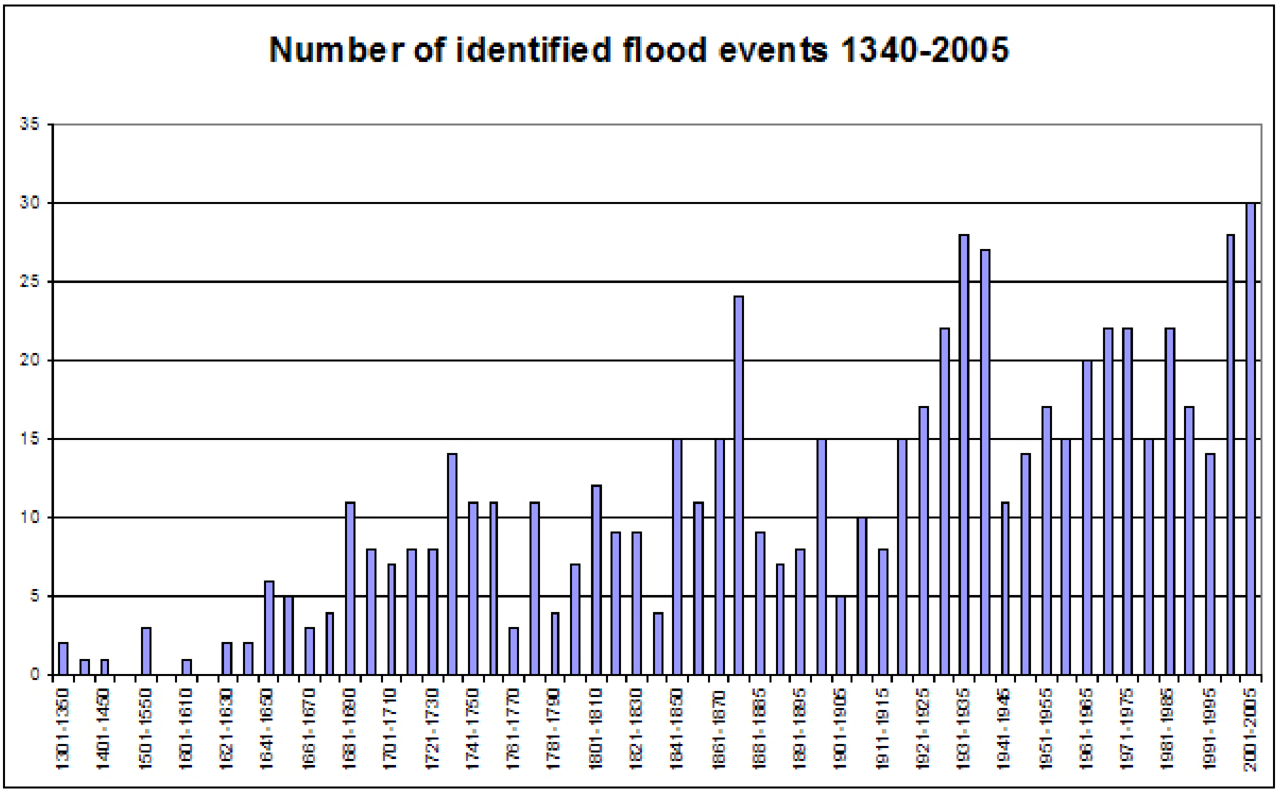


Figure 3.1 *The number of large floods in Norway based on documentary sources and instrumental data. The increase over time reflects the availability of information. Early events are only known from a few written and anecdotal sources. The earlier floods are always severe as smaller flood events would not have been recorded. Information on recent floods is based on direct observations in addition to reports, books and newspapers.*

3.1.3 Snowmelt floods

The major inland rivers in East Norway and in Trøndelag have been affected by a number of large floods in the spring or the early summer see Table 1 in Appendix 2. Many of these floods have occurred after a cool spring with a fairly rapid rise in the temperatures combined with some rainfall. Almost all floods in Troms and Finnmark are also spring floods caused by melting of the snow storage simultaneously over large areas. Figure 3.2 show the number of snowmelt or combined snowmelt rainfall floods and the number of rainfall events in Norway 1881–2005. The number of snowmelt floods is generally less than the number of rainfall floods. The snow melt flood extends normally over large areas and over a prolonged period. Most inland basins have snowmelt floods almost every year, but most of these floods are so small that they have not been included in the statistics. Many rainfall floods are fairly local phenomena, and will occur independently. A number of large combined events have occurred in the central mountain area of South Norway. These events occur usually later than the floods in the major rivers as seen from Table 2 in Appendix 2.

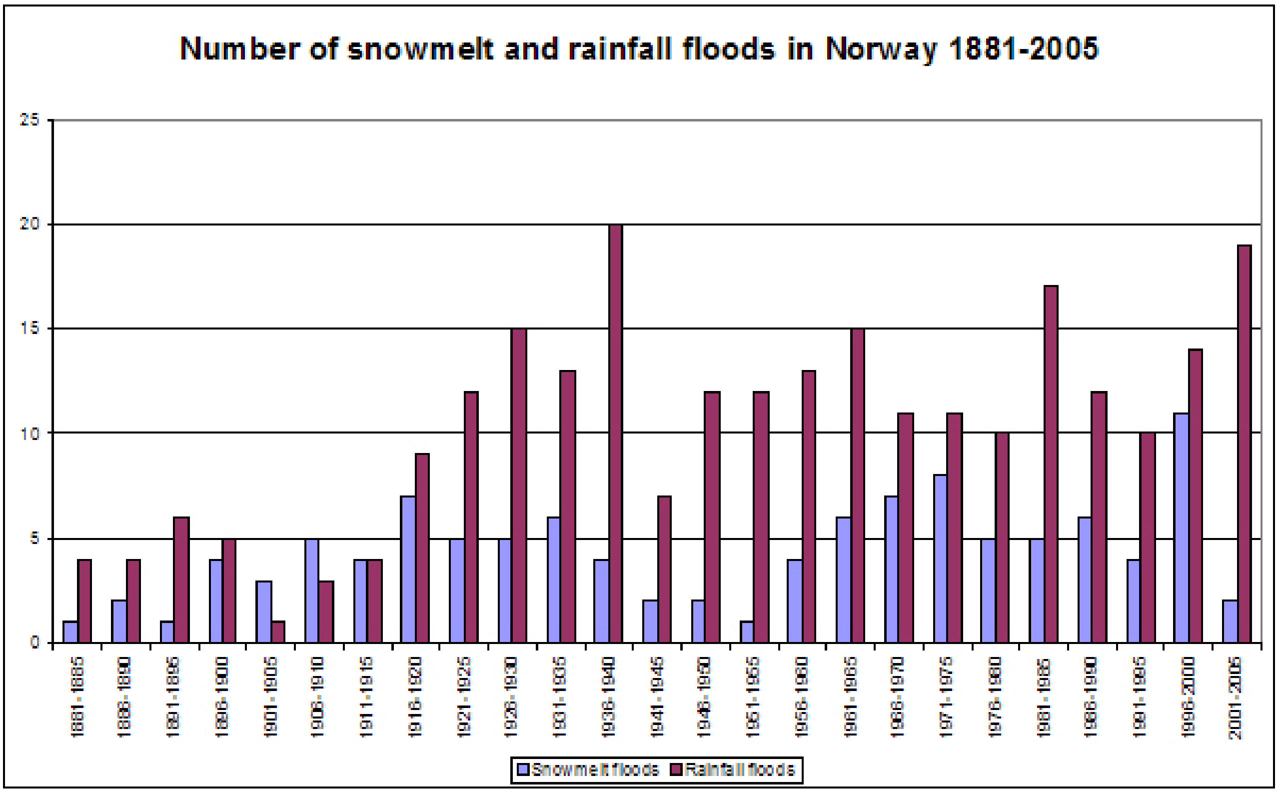


Figure 3.2 The number of flood events caused predominantly by snowmelt or rainfall per 5 year period in Norway 1881–2005.

Some of the most severe floods in West Norway are late autumn or early winter floods occurring after some accumulation of snow in the upper parts of the basin. The most extreme case of this type of floods occurred in December 1743, with deep layers of frozen soil after one of the most severe spells of the little ice age. The topsoil froze early because of a cold September–October, it was severe snow fall in November and torrential rainfall from 3rd–11th December, causing inundation, avalanches, landslides and rock-fall at many locations in West Norway from Ryfylke to Nordmøre. Other events are more local, but can cause severe damage such as the floods 15th–16th October 1842 and 7th–10th October 1883 at Valldal at Sunnmøre and Øksendalen at Nordmøre. Table 3 of Appendix 2 comprise a list of large late autumn or early winter floods in West and Central Norway. Mild winters can also cause multiple winter floods in the lower part of the major rivers in East Norway. The winters 1988/89 and 1989/90 were extremely mild and wet. The floods in January–February caused an enormous loss of top-soil. These winters are typical for the conditions that the scenarios indicate will be more common in a future warmer climate.

3.1.4 Rainfall floods

Rainfall floods can either result from long-duration rainfall, typically in the autumn or from local intensive convective rainfall events. Typical examples of the former are the autumn 1983 with up to 1100 mm rainfall in October in Sogn and the autumn 2000 with long-duration rainfall from September–November, causing flooding in smaller coastal rivers along the Oslofjord.

Some high-intensity rainfall events cover large areas and lasts for several days. One of these was Storofsen with intensive rainfall 21st–23rd July 1789. The peak of the large flood in 1860 was also caused by widespread intensive rainfall 15th–17th June although the large duration and enormous volume was caused by snowmelt. The flood in 1938 was also caused by a rainfall event lasting from 28th August – 2nd September. The upper part of Gaula and Orkla was badly affected by the disastrous rainstorm 24th–25th August 1940 causing destruction of the railway line at Støren as well as roads, farmland and buildings. The rainfall was even higher at Atnasjø, but the attenuation in the lake caused the resulting flood to reach the levels of only a 10-year return period flood.

The warm 1930s had an overabundance of intense rainfall floods, many quite local. A similar pattern has appeared from 1987 to present. Remnants of two tropical hurricanes (Maria and Nate) caused intensive rainfall in the Bergen area 14th–15th September 2005 resulting in flooding and killing landslides, and another event of different origin hit the same area 15th November same year with similar consequences. A large winter rainstorm hit the Fosen peninsula 30th January – 1st February 2006, with very high rainfall causing severe flooding. This event had a counterpart 28th–29th January 1932 in the same area. The local rainstorm with flooding and landslides 30th August 2006 at the border of Vågå and Lom is another example of a very local recent rainstorm, and show the consequences of extreme rainfall in areas with very low annual rainfall. This event had however also local counterparts in the same area during Storofsen, the 1860 and the 1938 floods.

Changes in rainfall statistics have been studied by Alfnes & Førland (2006).

3.1.5 Floods linked to glaciers

The discharge in glacier streams peaks normally late in the summer and tend to be high in warm summers at a time when rivers without glaciers tend to be low. The largest flood in the 105 year long series at Lovatn

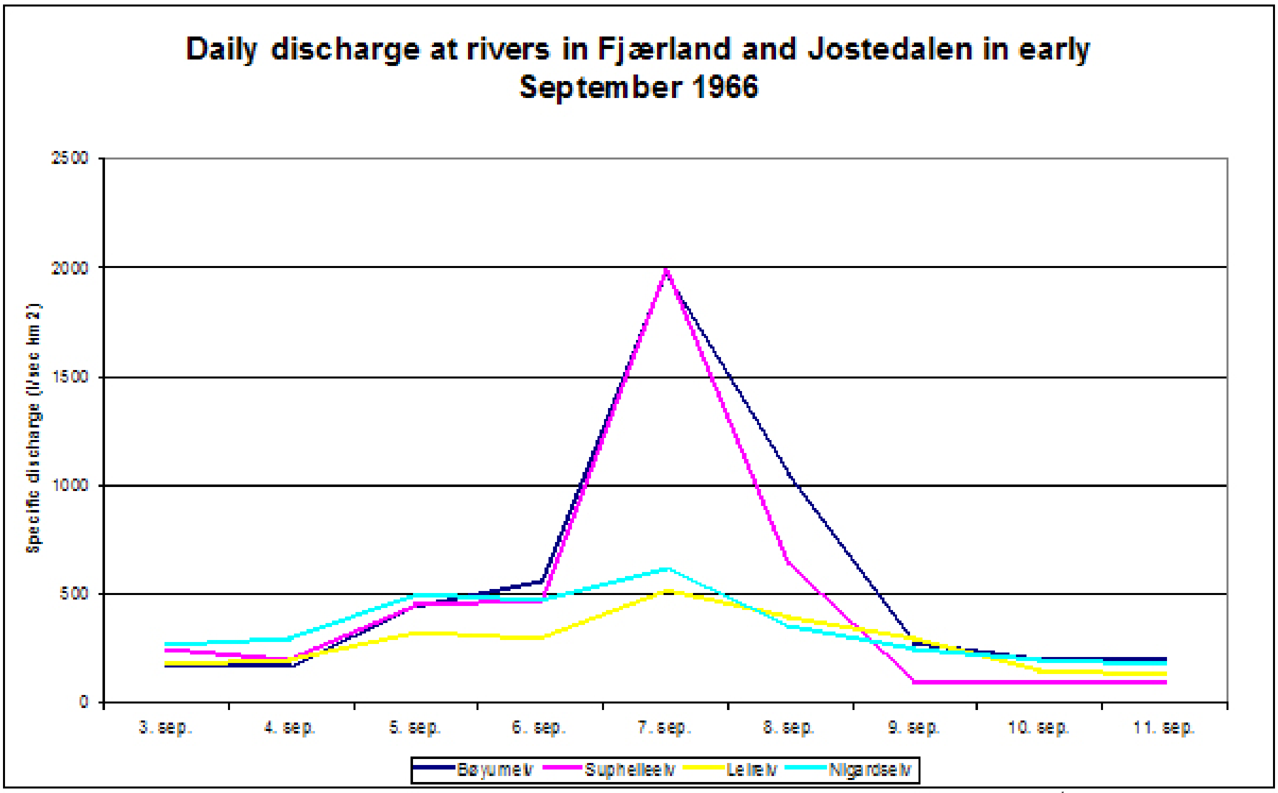


Figure 3.3 Observed flood at Fjærland caused by the remnants of tropical hurricane Faith 7th September 1966.

and Oldevatn occurred in 1941, a year which was very dry in rivers without inflow from glaciers. The warm and dry summer of 2006 is another example when non-glacierized rivers dried up, while glacial rivers flooded. The most effective melting occurs however when warm and humid air masses strikes a glacier. The remnant of the tropical hurricane Faith hit West Norway 7th September 1966 causing up to 200 mm rainfall over two days in Sunnfjord and intensive melting on parts of Folgefonni, Jostedalsbreen and the southern part of Ålfotbreen. Figure 3.3 shows observed specific discharge at Bøyumelven in Fjærland during this event, which is the largest observed flood in 40 years. Another system carried warm and humid air masses over Jostedalsbreen and caused heavy rainfall and flooding in Jostedalen 1979. Table 7 of Appendix 2 summarises some large floods in glacier streams in Norway.

River Sima has in the past suffered from many floods from glacier-dammed lakes (Elvehøy et al, 2002), as well as rivers on the east side of Folgefonni, Jostedalen from Brimkjelen at Tunsbergdalsbreen, Muldalselven at Sunnmøre and Rana from Lake Svartisvatn. By constructing diversion tunnels these lakes are no longer causing floods.

Recently two *jökullhlaups* have occurred at Blåmannsisen glacier in Nordland. The breakthrough of about 40 000 000 m^3 of water through the ice barrier in 1 ½ days is assumed to be linked to a thinning of the ice, which is directly linked to changes in the mass balance and to climate variability (Engeset et al., 2005, Engeset et al., 2006).

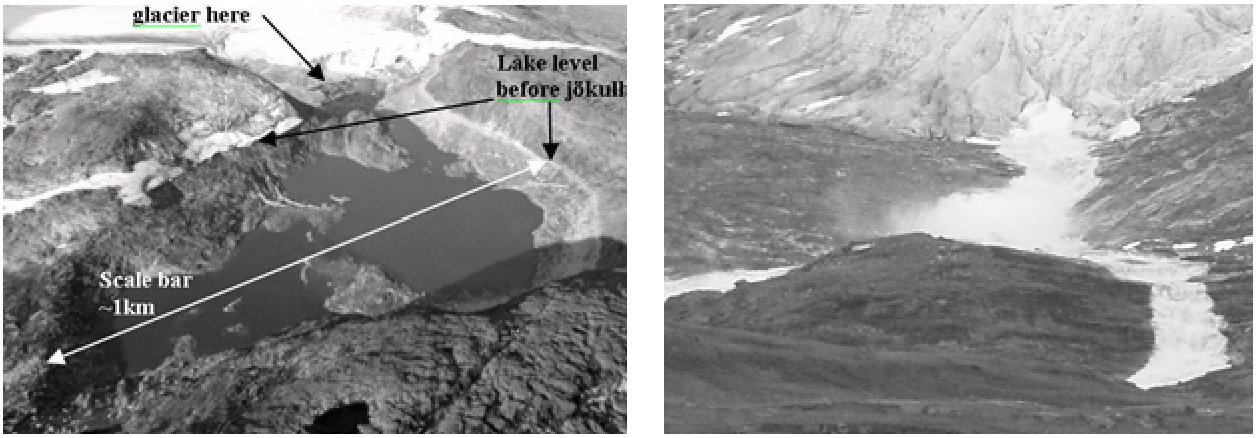


Figure 3.4 *The* jökullhlaup *at Blåmannsisen in 2001 (left) and 2005 (right), by Hans Martin Hjemaas.*

3.2 Man-made changes in the flood regime

3.2.1 Flood magnitude and the properties of the basin

The flood magnitude is strongly dependent on the physiography of the upstream basin. A good measure of the flood magnitude is the specific runoff, e.g. the runoff per basin area usually given in the unit l/sec km^2. The specific runoff is to some extent dependent on the size of the basin as well as regionally on the snowmelt and rainfall regime, but is also dependent on the amount of lakes and other landscape elements which would attenuate the floods. The major floods in rivers as Glomma (42 000 km^2) would hardly exceed 100 l/sec km^2 at the outlet even under floods like Storofsen while small basins along the coast of a few hundred km^2 may exceed 2000 l/sec km^2 during intensive rainfall. The specific runoff at the Lalm basin in River Otta (3900 km^2) was estimated to 420 l/sec km^2 during Storofsen, 400 l/sec km^2 during the 1860 flood and 358 l/sec km^2 during the flood in 1938. The lack of flood attenuation was clearly seen in River Gaula in Trøndelag (3000 km^2) during the flood disaster 24th August 1940, when the river peaked at 3000 m^3/sec or 1000 l/s km^2 while the mean discharge of the day was estimated to 1200 m^3/sec or 702 l/sec km^2.

Water levels was traditionally observed manually once a day, and the corresponding flood discharge was estimated using the stage-discharge curve, which was established from corresponding measurements of the water level and the discharge. Gradually recording instruments have been taking over the measurements resulting in much higher time resolution and the possibility of determining the actual peak value. The mean daily discharge have been estimated from the recording instruments and have been stored at the data base in a table of daily values together with the data read once a day. Basins with lack of attenuations as in River Gaula mentioned above can have a substantial difference between the daily value and the instantaneous peak value within the same day. Figure 3.5 illustrate this for the October flood in 1987 in River Grytbekken, a flood event caused by intensive rainfall after a long wet period, causing the ground to be saturated. The basin area is only 6 km^2 and show the difference between instantaneous and daily mean values that can be expected in a small natural basin, even with a small lake causing some attenuation.

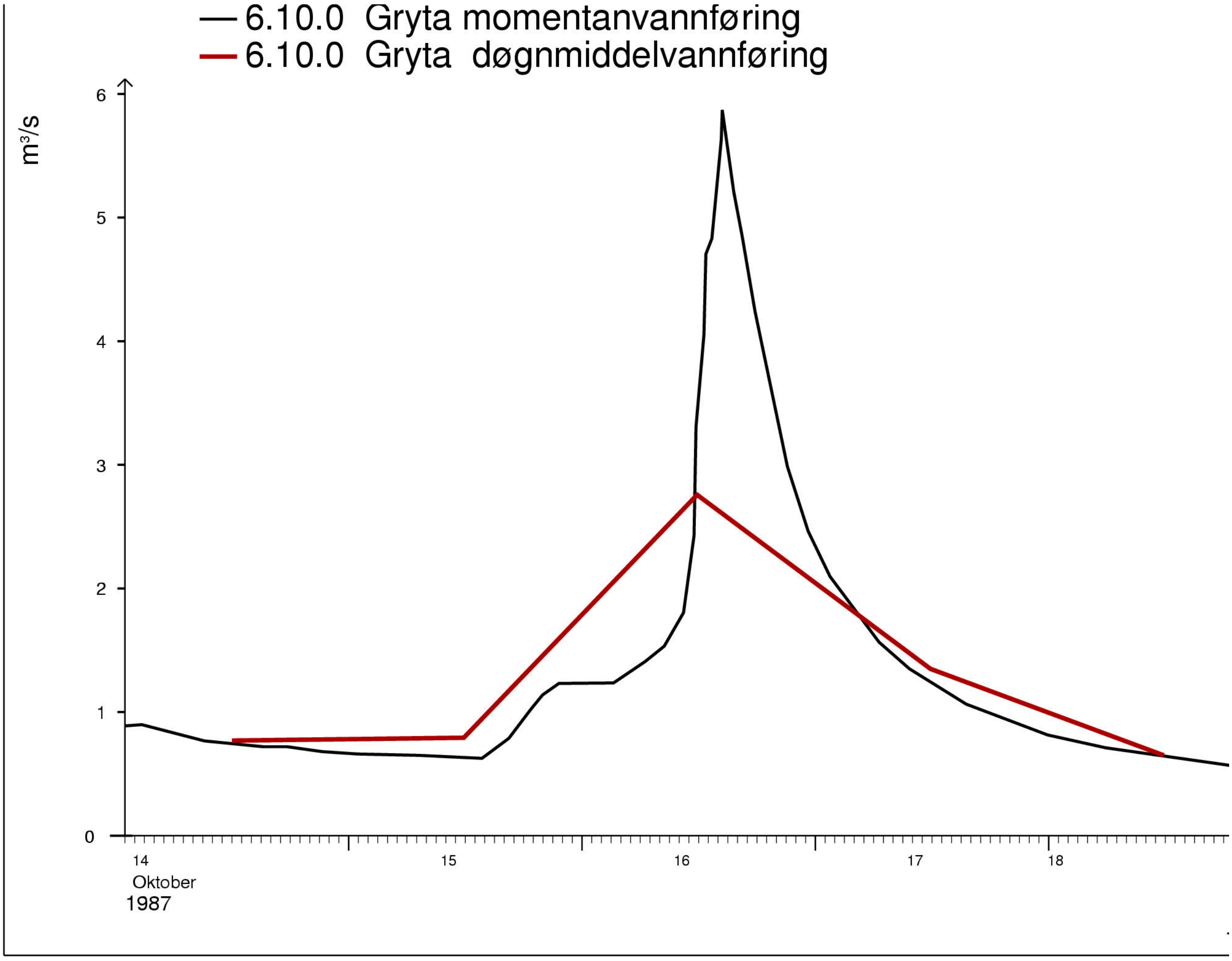


Figure 3.5 *Instantaneous (black line) and daily mean (red line) discharge at Gryta during the rainfall flood 16th–17th October 1987.*

3.2.2 Land use changes

Since the flood magnitude depends on the ability of the upstream basin to attenuate the flood wave, changes in the land use can affect the floods even under constant climatic conditions.

Urbanisation

The most severe changes in the peak flood occur when a previous natural basin is covered by impervious surfaces. Extremely urbanised areas have produced the highest specific runoff observed in Norway, as in the tiny Vestre Vika basin in Oslo with 96 % impervious surfaces and a peak value of 11.000 l/sec km^2 during an intense thunderstorm in 1975.

Large floods in the major water courses have caused severe urban flooding in towns next to the main river in the past. The towns around Lake Mjøsa have suffered from floods such as the 1860 and the 1995 floods. Lillestrøm have suffered flooding repeatedly during Storofsen, the 1860, the 1910, the 1916, the 1934, the 1966, the 1967 and the 1995, although the flood levels were gradually reduced by improving the capacity of draining Lake Øyeren at Mørkfoss. Kongsberg have also suffered from floods in Numedalslågen and Skien in parts of the town during large historical floods in

Skienselv. The regulations have reduced the risk of these floods. Rainstorms have caused several urban floods in recent years.

A possible cause of future damage is the new semi-urban development of recreation areas on the upper mountainous slopes in the inland. Some of these developments have been located at sites where intensive rainfall events have occurred in the past, even causing landslides with fatalities. The access roads can cause severe problems if new extreme events should occur, especially if the dimension of the culverts is insufficient.

Afforestation/Deforestation
The floods tend to increase after the clear-cutting of a forested basin. Macklin et al. (2005) have found major increase in flooding linked to the periods of major deforestation at the introduction of large scale farming in Britain from paleoflood data. The extensive use of timber for the copper mining at Røros in the 17th Century seems also to be linked to an increase in the occurrence of floods in the Upper Glomma basin. Afforestation can result in reduced peak floods, both as a result of increased evapotranspiration and less effective melting of the snow. The tree limit is expected to increase both as a result of the end on extensive domestic grazing and of climate change. Change in farming practices can also amplify or reduce floods (Eikenes et al. 2000). Levelling hills for grain production in connection with closing of brooks can pose a hazard as the drainage system ages.

3.2.3 Regulation

The major cause of man-made changes of the flood regime in Norwegian rivers is however consequences of hydropower development.

Diversions
Large scale diversions in or out of a basin can lead to significant increase or reduction of the annual flow and the floods as shown in Figure 3.6.

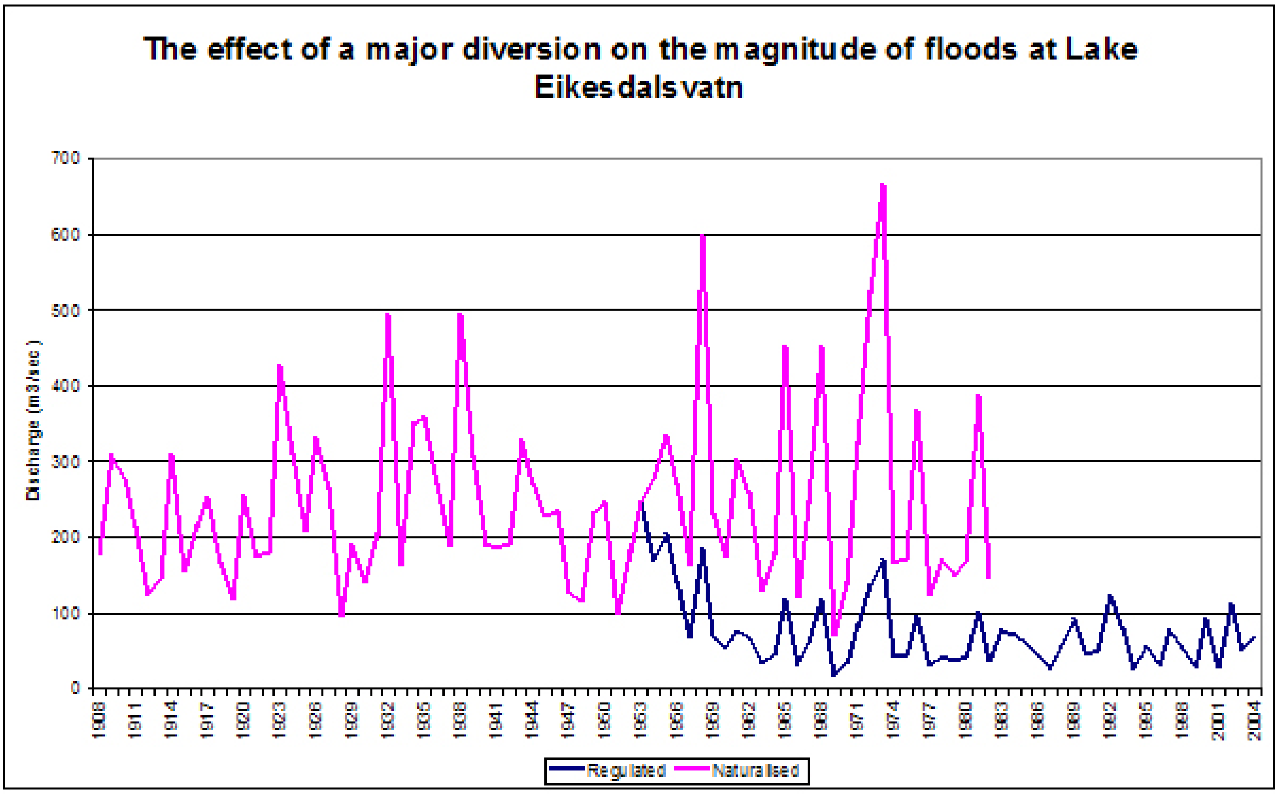


Figure 3.6 *Annual floods at the outlet of Lake Eikesdalsvatn in River Eira. A major part of the basin was diverted to the neighbour river from 1953, and the outflow is released from the power station there close to the sea. The naturalised flood series was calculated by adding the discharge used for hydropower production to the observed regulated flow series and correcting for the varying volume of the reservoir.*

Effect of reservoirs

The flow in Norwegian rivers has normally a peak in the spring or early summer as a result of the snow-melt. There is a secondary peak in the autumn in many regions, mostly caused by rainfall. Most of the energy consumption occurs in the cold season when the natural inflow to the power stations is low. Reservoirs are used to store the excess in the warm season to the winter and lead to a redistribution of the flow over the year. Figure 3.7 illustrates this for the large Møsvatn reservoir with typically a dominant flood in the late spring or early summer prior to the regulation. With multiple reservoirs the floods generally are reduced, and the low flows are increased. The reduction of flood magnitudes in a basin with moderate and large reservoir capacity is illustrated in Figures 3.8 and 3.9. Rainfall in the autumn on full reservoirs can increase the flood downstream, and the reduction in magnitude is often less during severe floods than during small flood events.

The reservoirs are mostly situated in the upper part of the major regulated rivers. The hillsides of the major river valleys are usually not affected by regulations. The snow accumulating in these slopes can contribute to local flooding even in the main river. A recent event occurred in Hallingdal in 6th–7th May 2004, when high temperatures caused fast melting in combination with convective rainfall. This flood affected also Rjukan, Bøverdalen, Dovre and Suphellerelv, with flooding, ice jamming, threatening and partly destroying bridges and roads, and causing a moraine ridge damming a small lake to be overtopped and causing a flash flood downstream. These hillsides are the areas most affected by flash floods causing substantial local damage and even loss of life because of landslides.

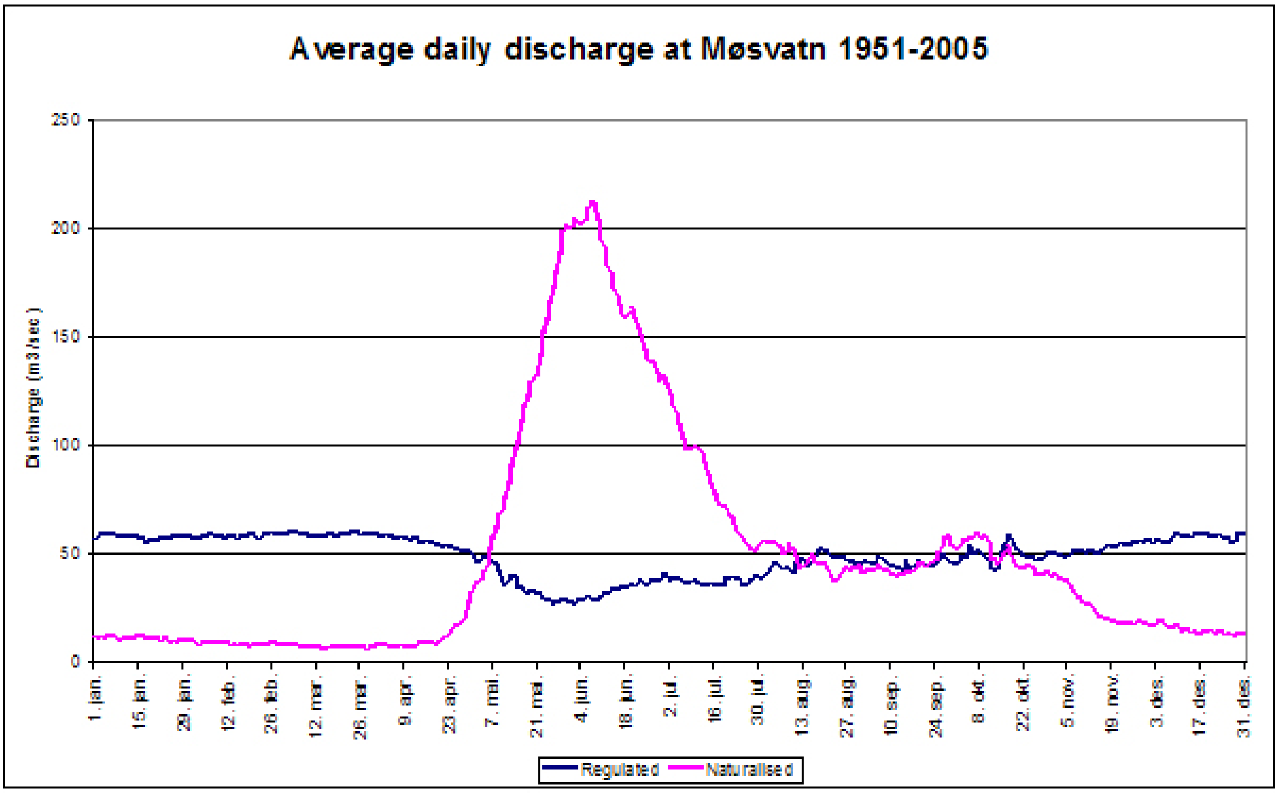


Figure 3.7 Large reservoirs can lead to a total redistribution of the regulated discharge over the year as shown for the Møsvatn reservoir where average daily values of regulated and naturalised discharge is shown for the period 1951–2004.

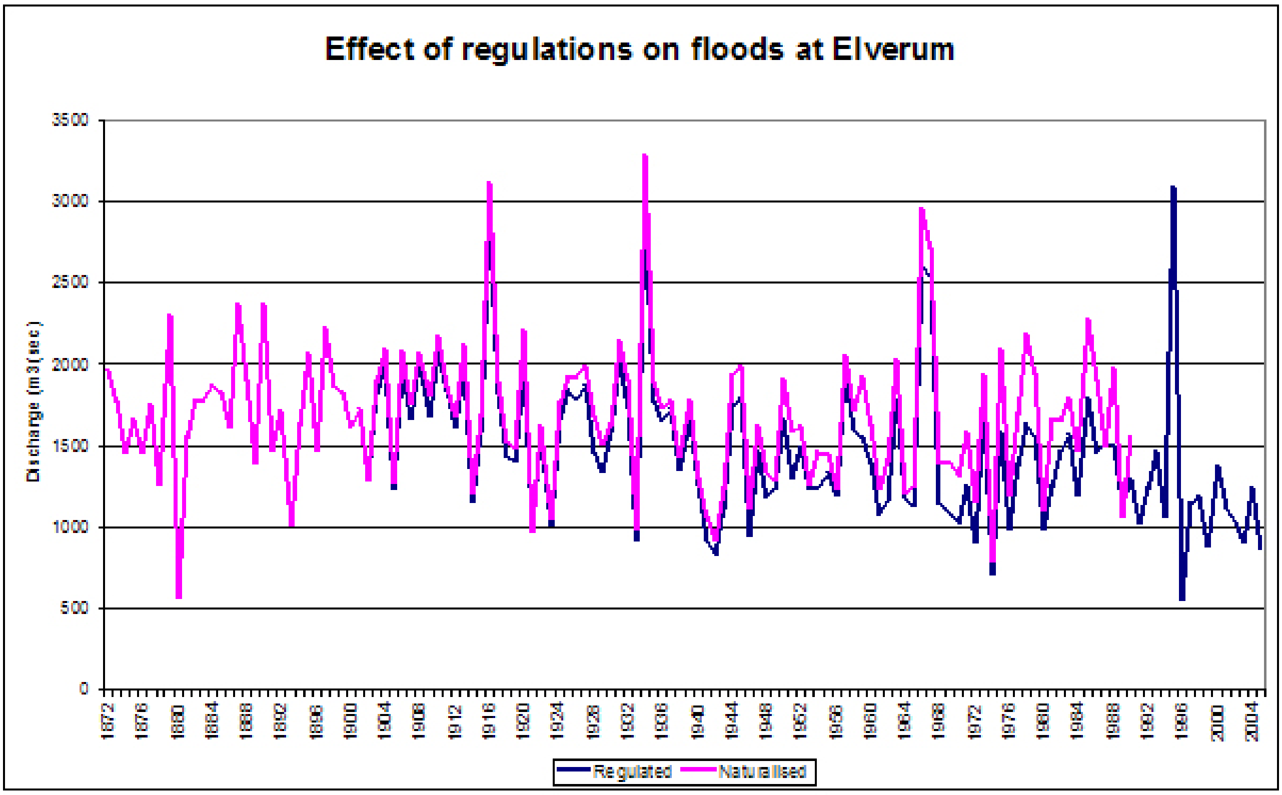


Figure 3.8 *Regulated and naturalised annual floods in River Glomma at Elverum. The degree of regulation is fairly low in the eastern branch of the river, but the 1995 flood would have exceeded Storofsen, if there had been no upstream reservoirs and preventive operation of the hydropower system as in 1789 (Tingvold 1996).*

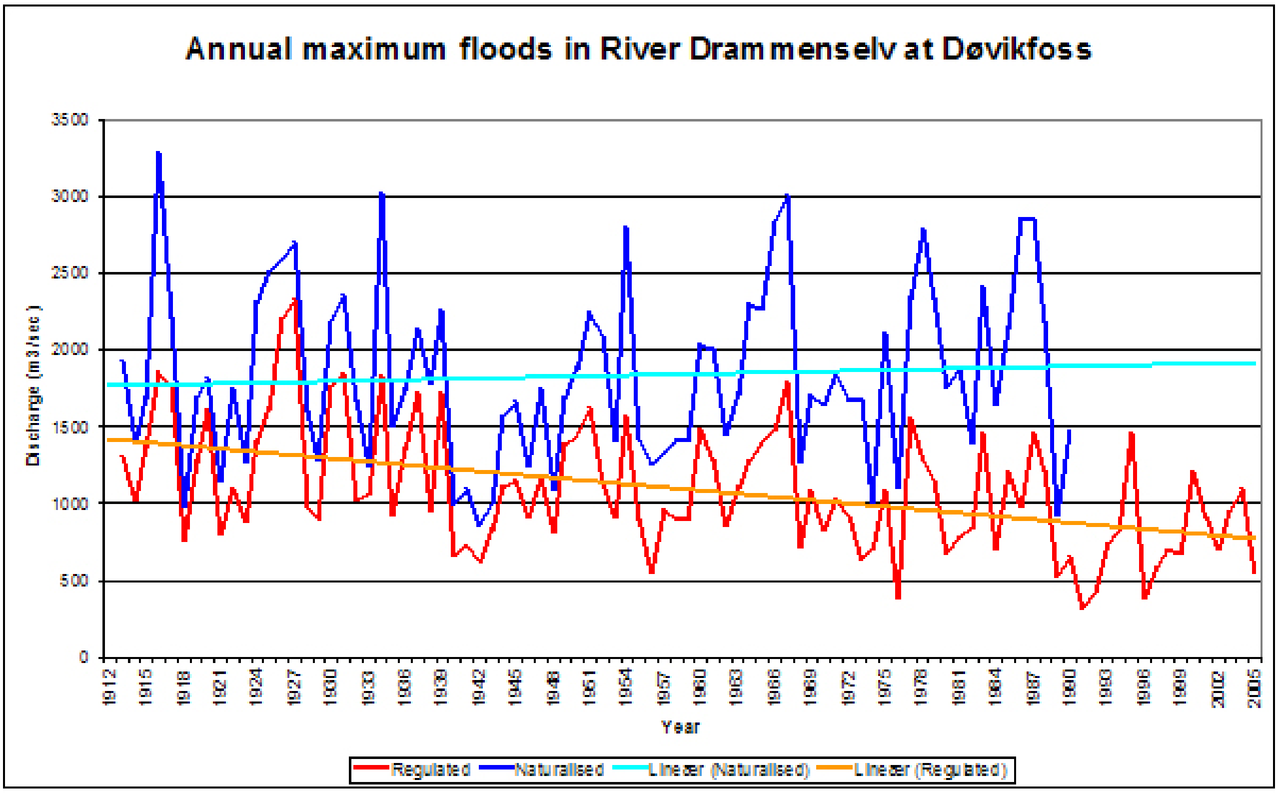


Figure 3.9 *Regulated and naturalised annual floods at Døvikfoss in River Drammenselv. The reduction in the flood magnitude is caused by 38 upstream reservoirs and the difference is typical of a heavily regulated water course.*

3.3 Flood damages

Flood damage comprises inundation of the flood plain with possible deposition of rocks, gravel, sand or trees on the inundated areas or erosion of the soil. After Storofsen in 1789, more than 4 m of material was deposited at farmland near River Orkla according to the damage reports. A frequent cause of damage is failure of the river bank. Floods in steep terrain can cause small brooks to grow and to cause landslides. This is well documented after Storofsen in Gudbrandsdalen and after the 1860 flood in upper Numedal.

While gradual flooding on the flood plain rarely has taken lives, flooding in steep terrain accompanied by landslides are far more dangerous. Storofsen which was characterised by multiple landslides, was reported to take 68 lives (Østmo, 1985), but a scrutiny of Church books indicates that the number of fatalities was at last 10 persons higher, and many people were saved under very dramatic circumstances. The flood in 1860 took around 12 lives in Drammenselva and Numedalslågen, mostly as a result of landslides, but also because of inundation near the main river. The flood in 1927 in Tinn caused also multiple landslides killing six workers at Rjukan.

Floods can erode river banks and will over time cause bank failures. NVE and its predecessor have repaired these banks and built flood protection works for at least 200 years (Andersen, 1996).

The economic consequences of the large floods can be devastating. The losses caused by Storofsen were estimated to 612 600 Rdlr in Glomma and Drammenselv only, and a total of more than 1300 farms and smallholdings were more or less damaged. The 1927 flood caused damages of 2.8 mill. NOK only in Telemark. The recent 1995 flood took one life, but caused damage of 1800 mill. NOK. A rainstorm 30th August 1996 caused damage on 250 houses in Kristiansand amounting to 15 mill. NOK. Rainstorms have caused several urban floods in recent years. Towns in Nord-Trøndelag suffered from an intensive rainstorm 21st July 2003 causing damages of some millions. The damage was enhanced by a storm surge from the sea; this occurred also in harbour areas around the Oslofjord 16th–17th October 1987, and recently several times in Bergen, most recently during the rainstorms of 13th–14th September and 15th November 2005. Heavy rainfall in urban areas is now causing more damage on the average than the widespread but rare major floods, reflecting increase vulnerability of the society and the infrastructure to cope with floods.

Dam failure have not been a severe problem in Norway, although there have been some incidents of minor consequences. An increase in autumn rainfall floods on full reservoirs can increase the risk of overtopping, and will be focused in further consequence studies.

3.4 Projected change in the occurrence of floods

3.4.1 Climate and hydrological scenarios

The hydrological modelling is based on daily series of temperature and precipitation data at some 80 climate stations for a control period 1980–1999 or 1961–1990 and a scenario period 2030–2049 or 2071–2100 provided by RegClim. The scenarios are based on results from two Atmospheric Oseanographic Global Models (AOGM), ECHAM4 and HadleyAm3H. These models operate with a typical grid size of 300 x 300 km^2. The results have been downscaled using the regional HIRHAM-model to grid size 55 x 55 km^2. The data have further been adjusted to climate stations (Engen-Skaugen, 2004). The climate models were driven by the SRES IS92a scenario for 2030–2049, a transient run 1980–2049 and the A2- and B2-scenarios 2071–2100.

Daily time series of the runoff, snow water equivalent and other water balance elements were simulated using the Gridded Water Balance Model (GWB) (Beldring et al., 2003). This model is a gridded version of the HBV-model operating with grid size 1 x 1 km^2. Data series can be established by integrating the output over all grid cells included in each basin under consideration. Results of the hydrological modelling have been presented in Roald et al. (2002, 2006).

3.4.2 Projected changes in the snow reservoir

The GWB-model produces daily series of snow water equivalent (SWE) for selected basins. The simulated SWE have been compared to data observed on two snow pillows, one in the Aursunden and one in the Møsvatn basins. The model seems to describe the day to day SWE values quite well, although there may be some difficulties in getting rid of all snow at the end of the melting season. Schuler et al. (2006) present results of the modelling and discusses uncertainties in the results.

Figure 3.10 show the median and the maximum and minimum SWE for each day in the year of the control and scenario periods at Aursunden for the two scenarios based on the Hadley model. The figure shows that the maximum value is reduced and the duration of the snow cover is substantially reduced. Beldring et al. (2006) show maps of SWE, duration of the season with snow cover and other water balance elements under present and future climate based on the A2 and B2 scenarios of the HadAm3H- model and the B2 scenario of the ECHAM4-model. The number of days with snow cover will be reduced by 20–35 days in inland basins to 80–100 days in coastal basins from Jæren to Finnmark. The maximum annual SWE will be moderately reduced, from close to 0 in inland basins to 40–60 % in some extreme coastal basins. These scenarios have been estimated for the scenario period 2071–2100.

Roald et al. (2002) present earlier scenarios based on the ECHAM4-model and only one emission scenario: SRES IS92a for the scenario period 2030–2049, using the more recent control period 1980–1999 as well as a transient run 1980–2049. The increase in temperature is less in this shorter scenario, and because of increasing winter precipitation in southern Norway, a surplus of snow is found in high mountain areas in east Norway. This indicates that there is a potential for large spring floods at least early in the period. The potential for large spring floods is much lower when the temperature rises sufficiently to cause minor flooding throughout the winter except in alpine basins. Heavy rainfall and optimal melting condition can occur earlier in the year when the hillsides still is covered by snow and can cause local flooding even in regulated watercourses as mentioned above.

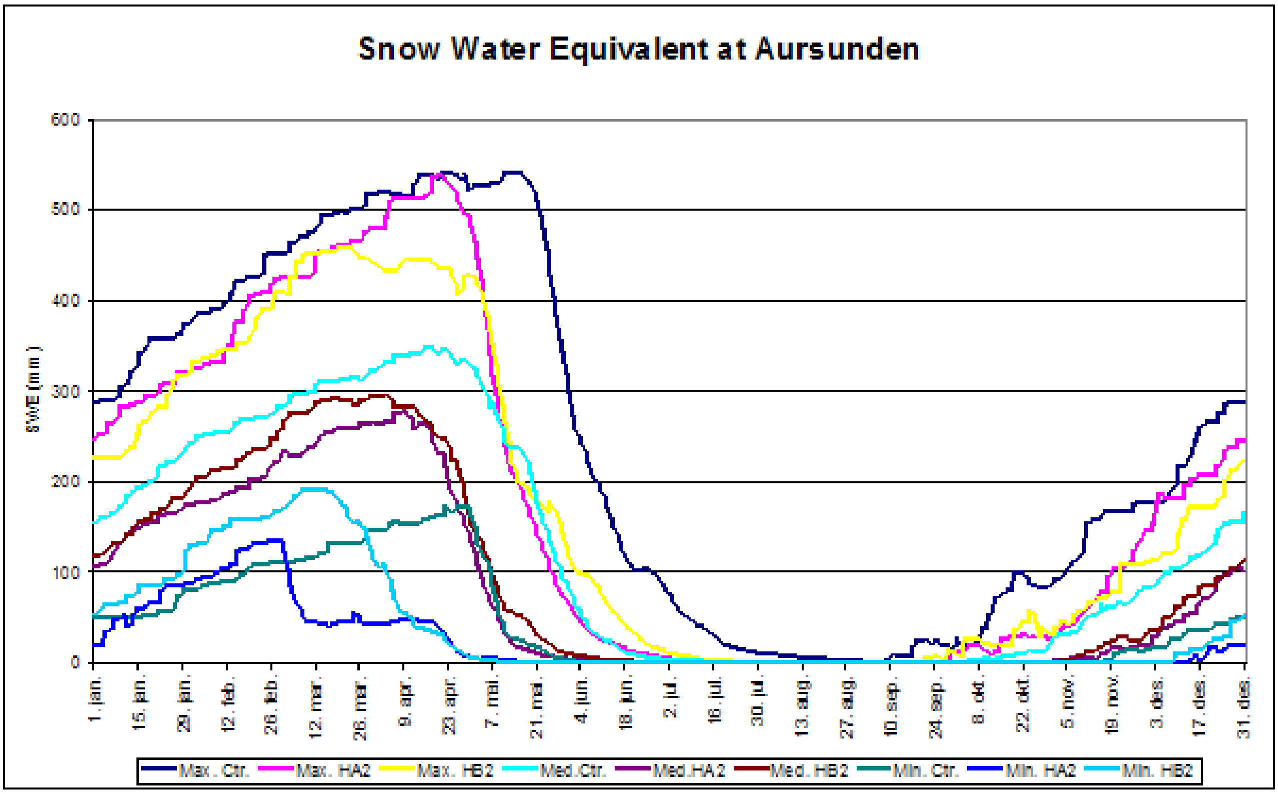


Figure 3.10 *Simulated Snow Water Equivalent (SWE) for the control period (1961–1990) and the scenario period (2071–2100) at Aursunden in Upper River Glomma. The figure shows the daily median, maximum and minimum value for the control period and the scenario period based on the A2 and B2 scenario of the HadleyAm3H- model.*

3.4.3 Projected changes in flood magnitudes and seasonality

The annual runoff will increase moderately in many regions, but the seasonal runoff pattern will change significantly, given the climate scenarios. The winter runoff will increase, both as a result of higher temperature and more mild spell during the winter and because the winter precipitation is projected to increase over much of Norway. The spring runoff will increase in high mountain areas, and decrease moderately in the lowland. The summer runoff will decrease almost everywhere because of reduced rainfall and increasing evapotranspiration. The autumn runoff will increase over much of Norway. The shift from spring to winter in lowland basins and from summer to spring in high mountain basins is partly caused by earlier melting of the main snow storage.

The natural variability in temperature and precipitation is quite high, and may dominate over the longer gradual trend in temperature and precipitation on a short term. The maximum annual snow storage is projected to decrease, but the length of the season with snow cover will decrease far more than the maximum value of the snow water equivalent. The snow storage may even increase in higher inland basins early in the scenario period as a consequence of increasing winter precipitation. These basins had fairly low winter temperatures in the control climate, and the gradual rise in winter temperatures would need to last for quite a number of years to cause the temperature to rise above freezing sufficiently to reduce the size of the maximum snow storage and hence the potential of large snow melt flood.

Changes in the frequency and magnitude of floods can be identified by comparing the flood statistics of two different time slices, a control period representing present climate and a scenario period. The shorter term scenarios applied the period 1980–1999 as control period and 2030–49 as scenario period. The 50-year return period flood was estimated for the annual flood for 17 basins based on the short term scenarios. The flood magnitude increases by 1–2 % for many of the basins, but some basins show either a larger positive or negative change. If the flood frequency analysis were based on the transient series based on gradual increase of the greenhouse gasses through the entire period 1980–2049, the magnitude of the 50-year flood was often significantly higher. Figure 3.11 show the transient flood series for Sjodalsvatn (Sjoa) and Risefoss (Driva) representing Jotunheimen and Dovrefjell. Figure 3.12 show two series Hetland (Ogna) and Stordalsvatn (Etneelv) representing the southwest coast. Nordland is represented by Nervoll

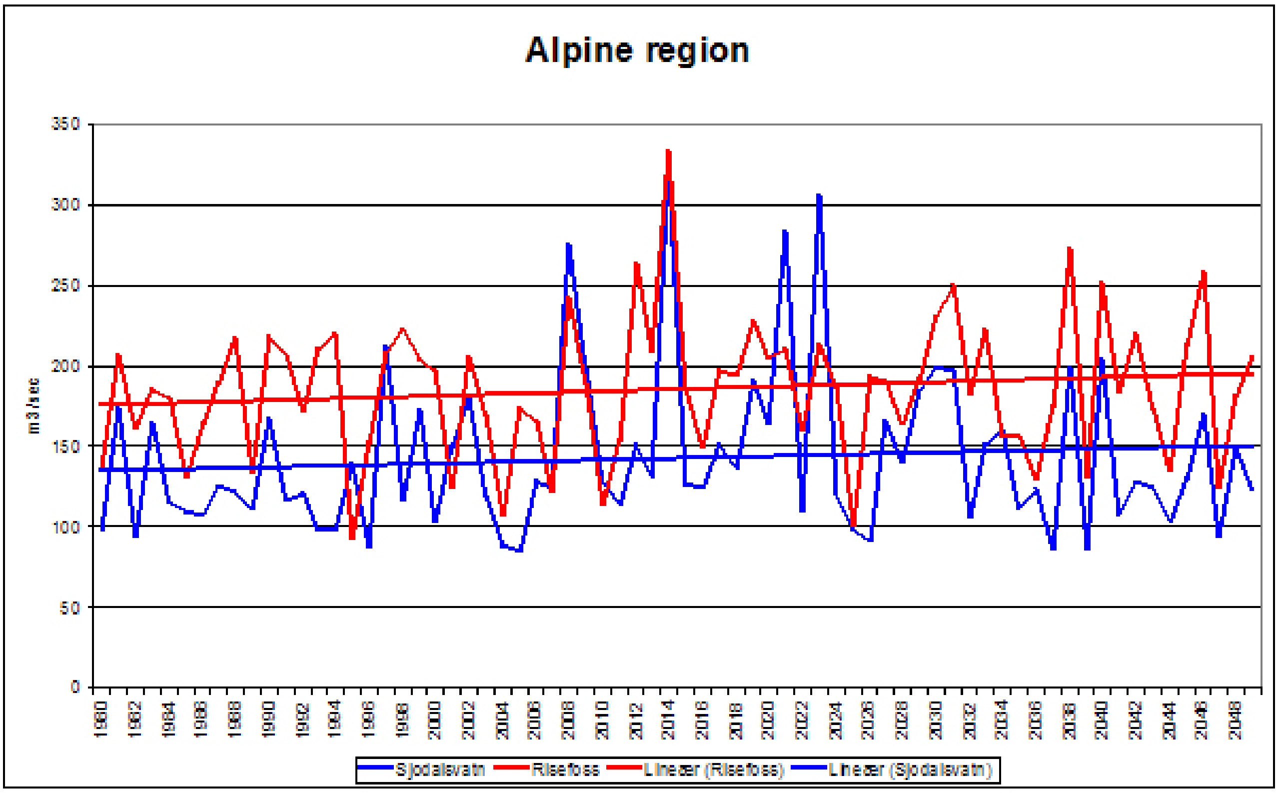


Figure 3.11 Variability of the annual flood in alpine basins in Norway based on a transient run 1980–2049 of the hydrological model driven by the ECHAM4/OPYC3 model, the IS92A emission scenario and downscaling by the HIRHAM model.

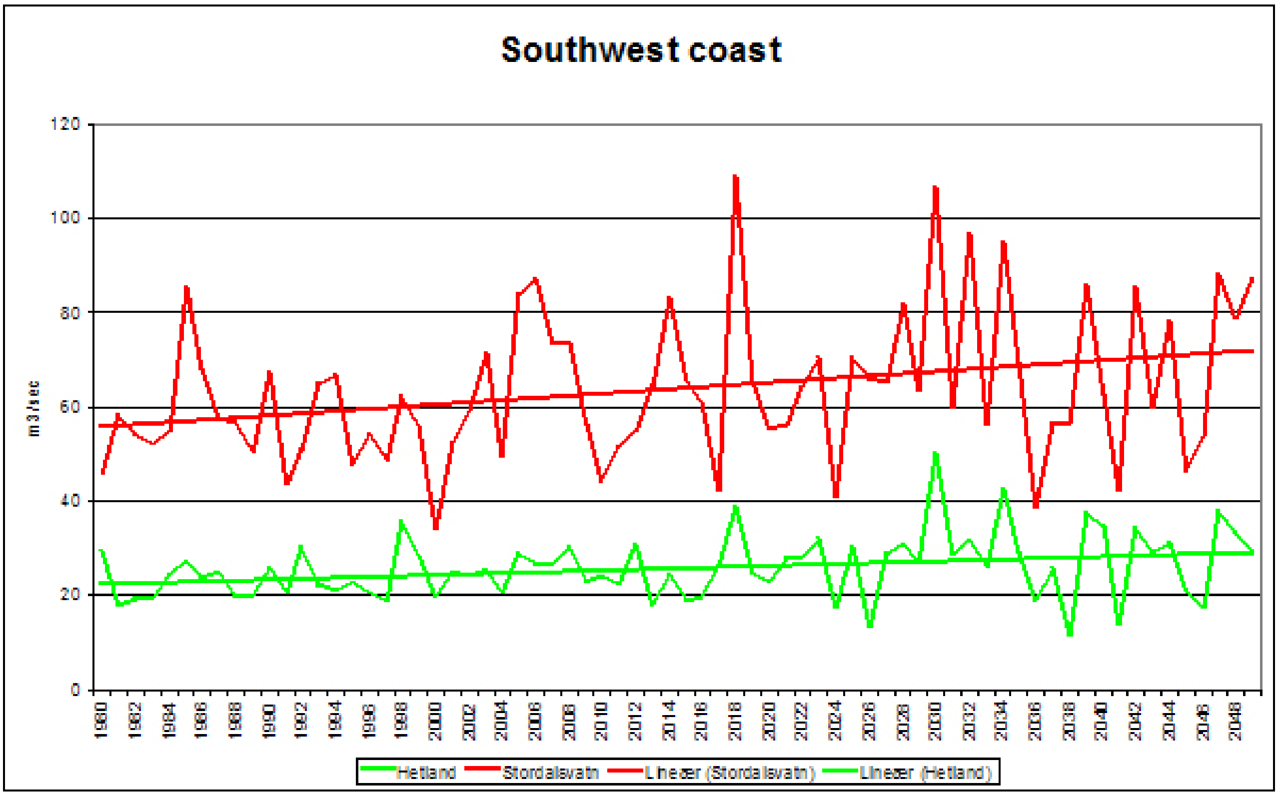


Figure 3.12 *Variability of the annual flood in basins at the southwest coast of Norway based on a transient run 1980–2049 of the hydrological model driven by the ECHAM4/OPYC3 model, the IS92A emission scenario and downscaling by the HIRHAM model.*

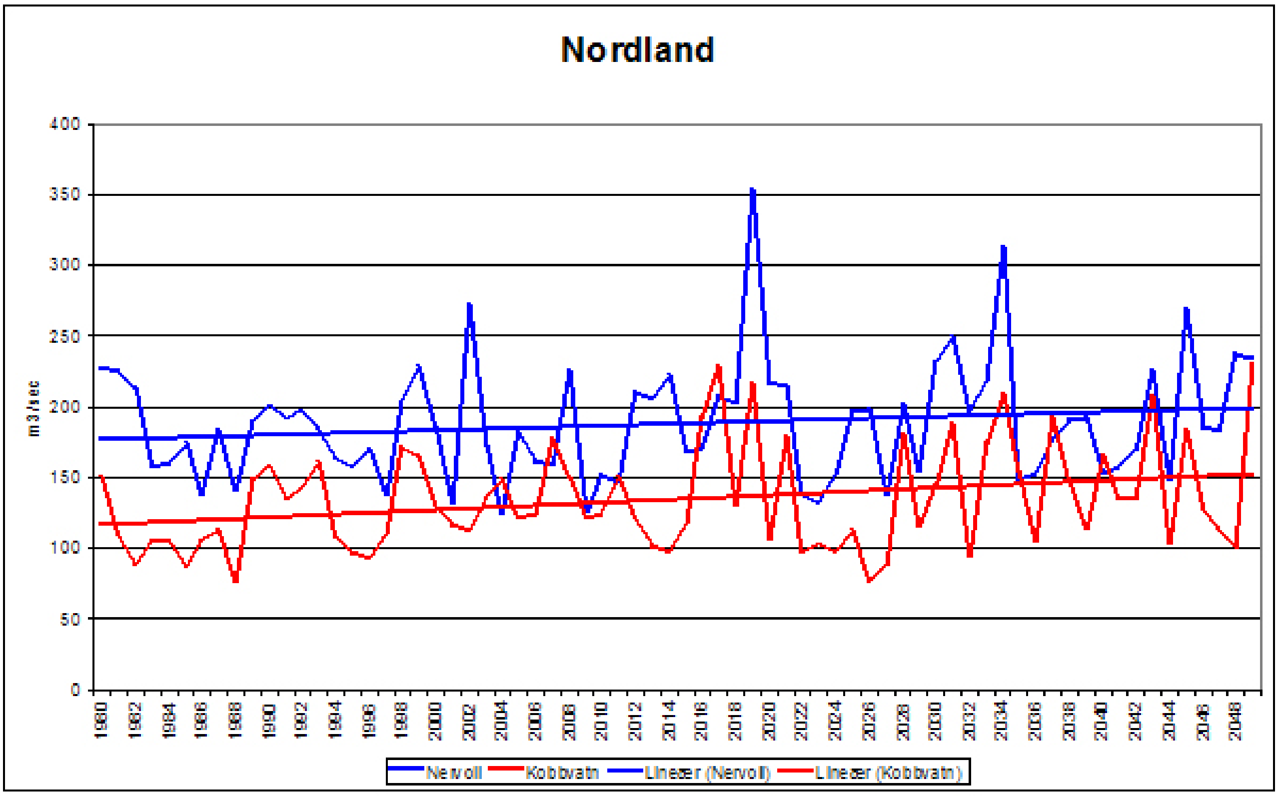


Figure 3.13 *Variability of the annual flood in basins in Nordland based on a transient run 1980–2049 of the hydrological model driven by the ECHAM4/OPYC3 model, the IS92A emission scenario and downscaling by the HIRHAM model.*

(Vefsna) and Kobbvatn (Kobbelv) in Figure 3.13. The figure shows the large year to year variability throughout the full transient period. If alternative 20-year periods used as basis for the analysis, higher flood magnitudes are found. The 20-year samples are obviously not able to represent the large natural variability of the floods. The effect of increasing content of green-house can induce a possible trend, which is easier to identify when the long term scenarios are used as basis for the comparison.

The adjustment of the downscaled climate series was improved before the scenarios for 2071–2100 were made (Engen-Skaugen, 2004), and the hydrological model was recalibrated to obtain a more representative parameter set, than used in simulating the 1980–2049 scenario. The changes in annual and seasonal flood characteristics described below are therefore based on the long term scenarios with 30 year time slices of control and scenario period.

Changes in the occurrence of rainfall floods depend on changes in the dominating atmospheric circulation patterns as well as the occurrence of local convective storm cells, of a scale too small for the climate models to describe well. The ECHAM4- and the HadAm3H- models project two different dominating circulation types over Fennoscandia. Because of the strong dependency of the distribution of rainfall on the trajectories of the precipitation areas (Tveito & Roald, 2005), a shift in the dominating circulation can result in quite different flood patterns in various parts of Norway. The ECHAM4 indicates increasing strength of the westerlies, causing increased rainfall along the west coast up to Lofoten, especially in the autumn. The HadAm3H-model indicates increased occurrence of precipitation events from east, and reduced increase of precipitation and runoff in the northern part of West Norway, and a reduction in Mid Norway.

A comparison of the daily circulation indices on days with heavy rainfall from the northern part of West Norway to Lofoten from the 1895 to 2004 show that most of the large west coast rainfall flood events are linked to weather types according Gerstergarbe & Werner (2005) or to Hulme & Barrow (1997) with extensions 1996–2004 from CRU characterised by high pressure ridges over the northern part of Continental Europe to the British Isles, with strong westerlies north of the high pressure ridges, reminiscent of the dominant circulation described by the ECHAM4-model. Other characteristic weather types linked to floods are dominating further along the southwest and southern coast.

Daily flow series have been calculated for 23 basins for the control period 1961–1990 and the scenario period 2071–2100 based on the HadAm3H model for emission scenario A2 and B2 and for the ECHAM4 model for the B2 scenario. The location of the basins is shown in Figure 3.14, and the number, names and river is listed in Table 3.1.

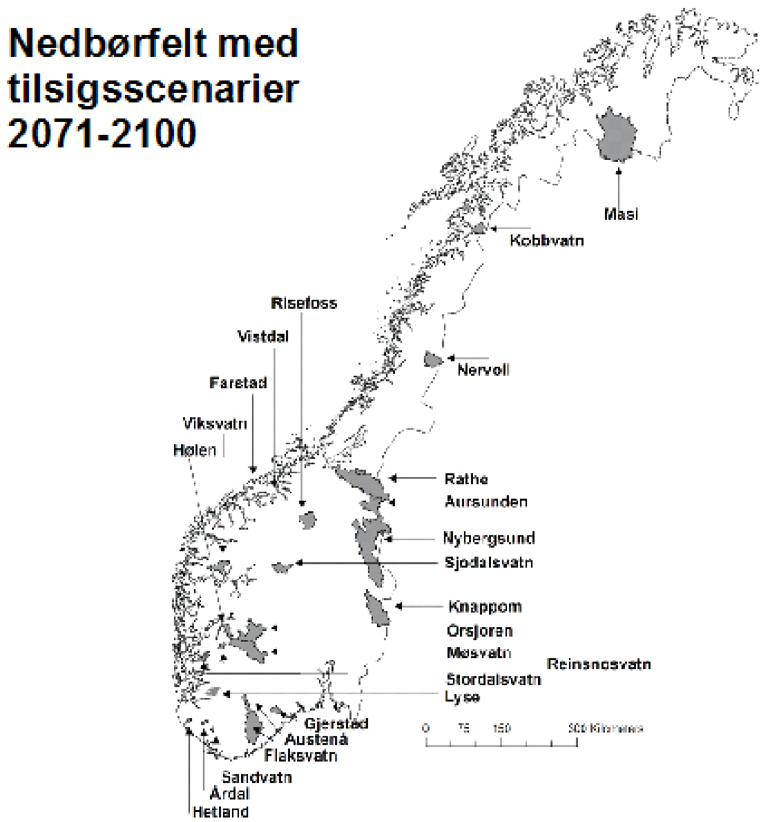


Figure 3.14 Location of 23 basins with daily time series for the control and scenario period.

Table 3.1 *Number, name and river of the 23 basins with daily flow data.*

Number	Name	River	Number	Name	River
311.6	Nybergsund	Trysilelv	48.5	Reinsnosvatn	Austdalselv
2.111	Aursunden	Glomma	50.1	Hølen	Kinso
2.13	Sjodalsvatn	Sjoa	83.2	Viksvatn	Gaular
15.79	Orsjoren	Numedalslågen	104.23	Vistdal	Visa
16.19	Møsvatn	Måna	107.3	Farstad	Farstadelv
18.10	Gjerstad	Gjerstadelv	109.9	Risefoss	Driva
20.2	Austenå	Tovdalselv	123.20	Rathe	Nidelv
26.20	Årdal	Sira	123.31	Kjelstad	Nidelv
26.21	Sandvatn	Sira	151.15	Nervoll	Vefsna
27.26	Hetland	Ogna	167.3	Kobbvatn	Kobbelv
257.257	Lyse kraftverk	Lyseelv	212.10	Masi	Alta
41.1	Stordalsvatn	Etneelv			

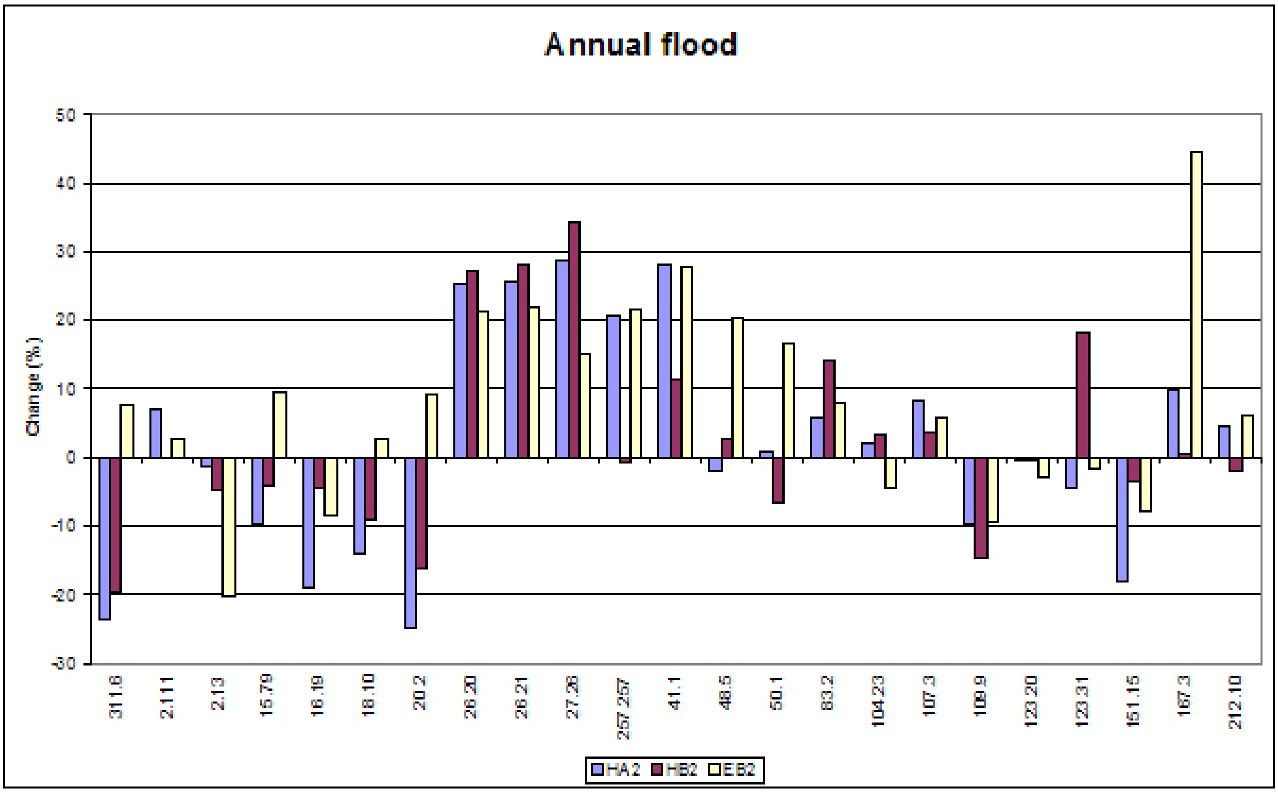


Figure 3.15 *Projected change in the 50-year return period annual flood in 23 basins in Norway. Basin no 311.6–2.111 are in East Norway, 2.13 and 109.9 are mountainous basins, 15.79–26.21 are in the southernmost part of Norway, 27.26–83.4 West Norway, 104.23–123.31 Mid Norway, 151.15–167.3 North Norway and 212.10 Finnmarksvidda plateau.*

The projected change in the 50-year return period of annual flood from 1961–1990 to 2071–2100 is shown in Figure 3.15. The calculated change is based on 30-year time series of daily runoff. The return period was estimated based on use of the General Extreme Value distribution fitted by the method of Probability Weighted Moments (PWM. Figures 3.16–3.19 show the projected change in 50-year return period for the winter, spring, summer and autumn seasons. The large percentage increase in the most mountainous basins during the winter is partly because the runoff is very low under the control climate.

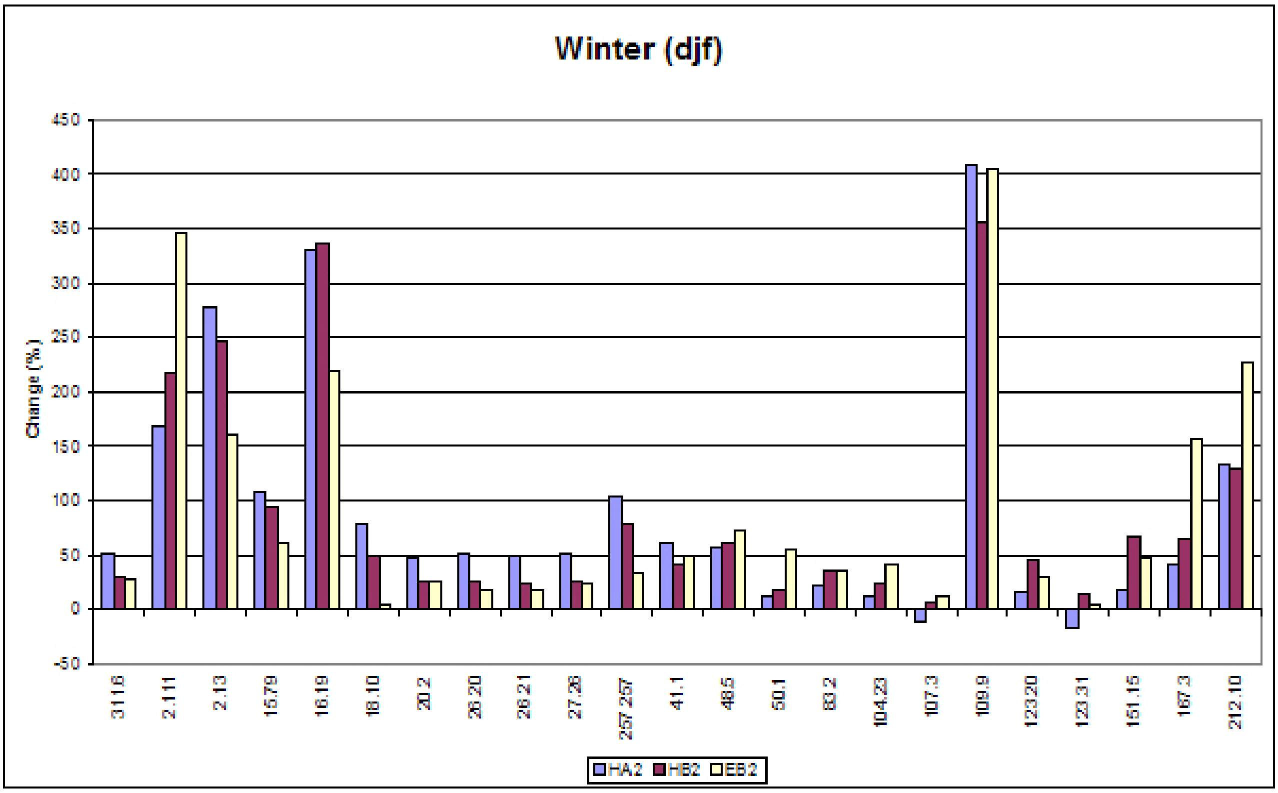


Figure 3.16 *Projected change in the 50-year return period winter flood in 23 basins in Norway.*

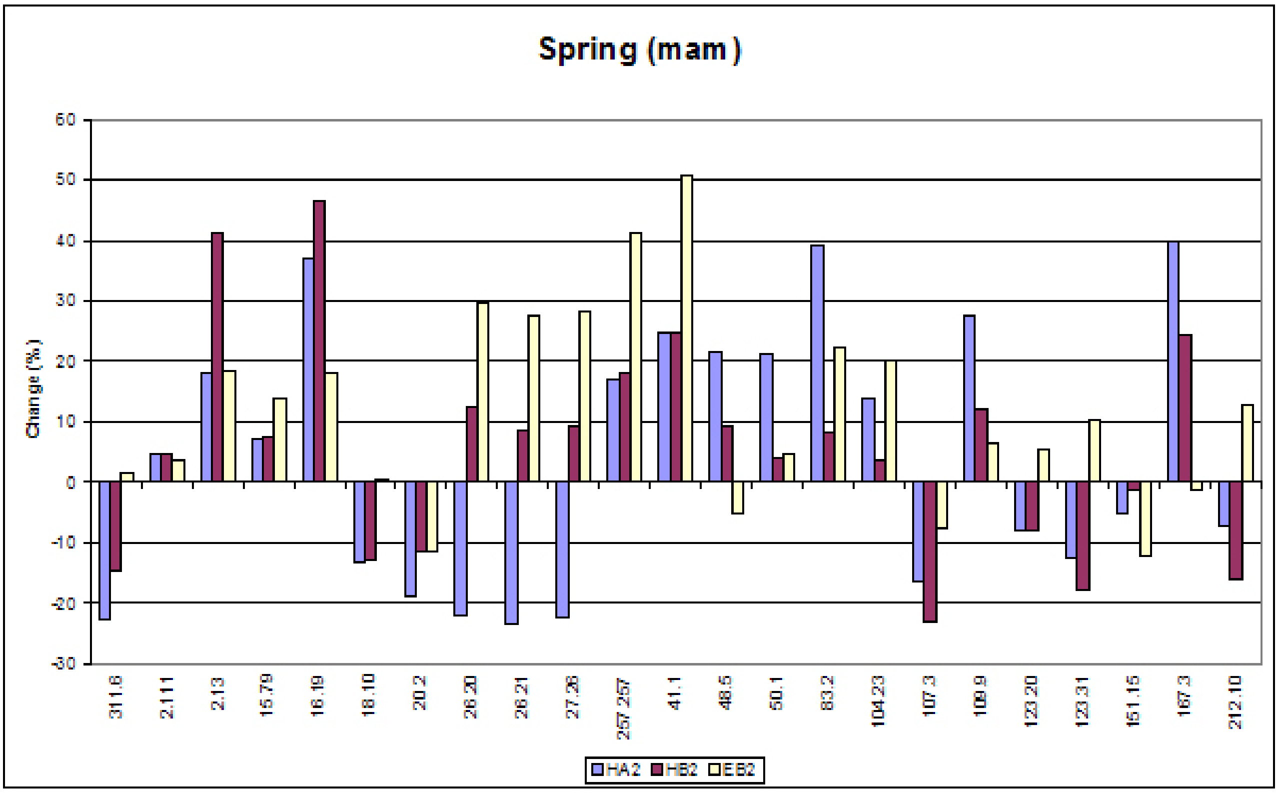


Figure 3.17 *Projected change in the 50-year return period spring flood in 23 basins in Norway.*

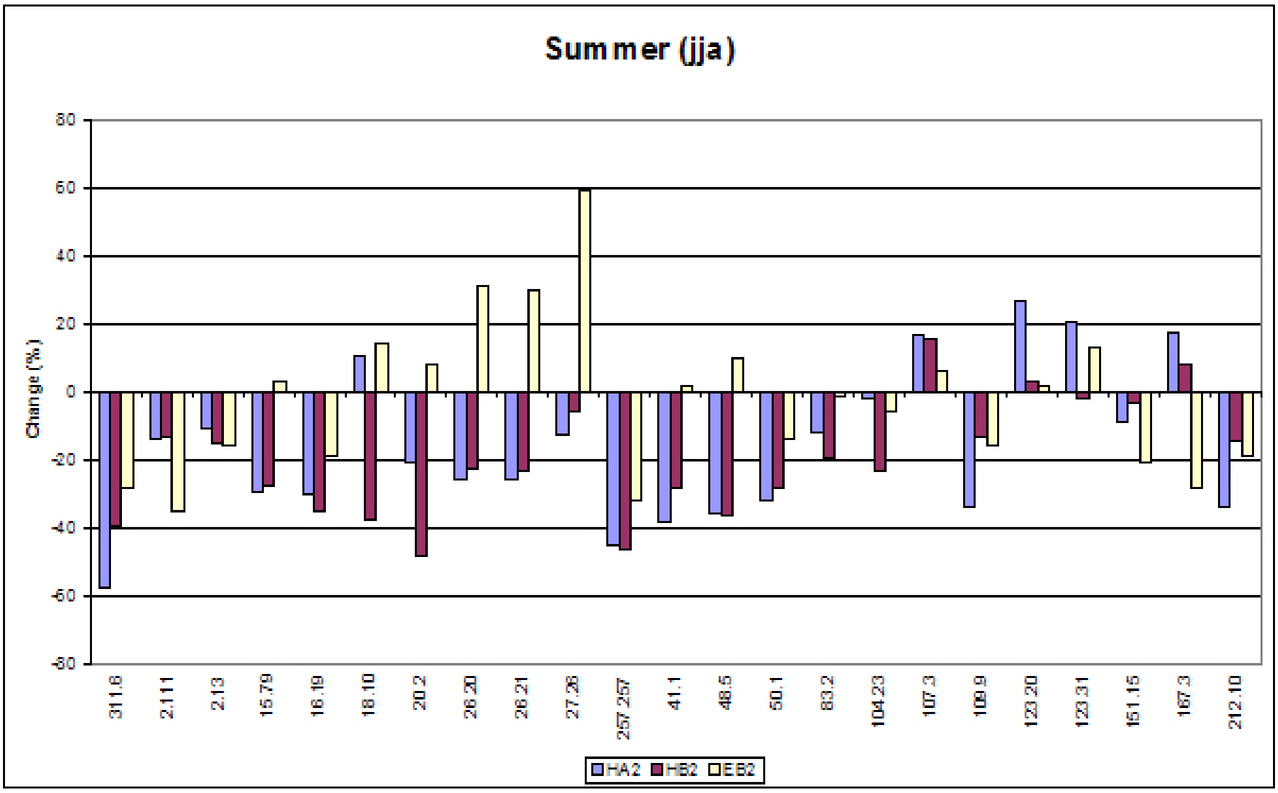


Figure 3.18 *Projected change in the 50-year return period summer flood in 23 basins in Norway.*

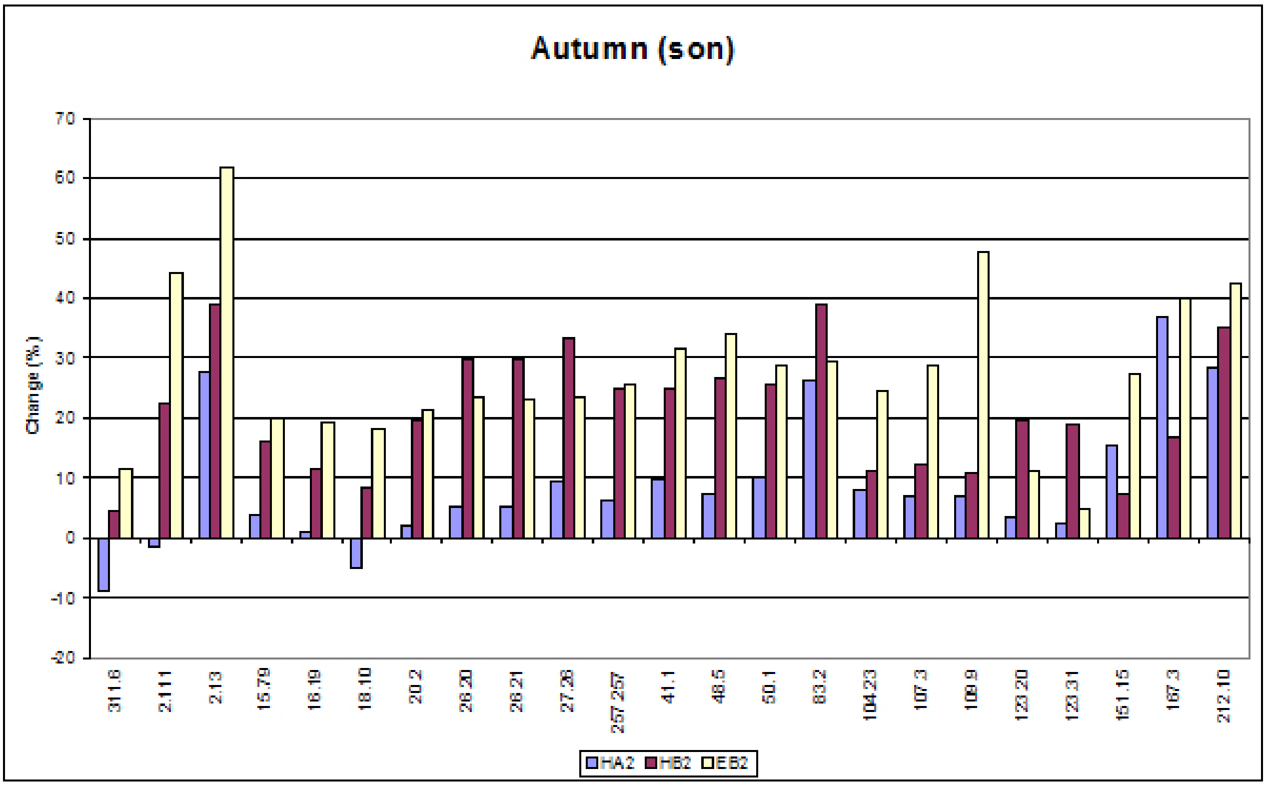


Figure 3.19 *Projected change in the 50-year return period autumn flood in 23 basins in Norway.*

The projected changes in the spring and summer reflect the shift in time of the peak of the snowmelt. Alpine basins are increasing significantly because the peak of the snowmelt shifts from early summer to late spring. The summer season has reduced floods partly because of the shift mentioned above, but also because of the inability of the climate models to simulate small scale flash floods. The autumn floods are increasing in the autumn because of increasing precipitation.

3.4.4 Changes in glacial rivers

Lappegaard et al. (2006) have examined the runoff in eight Norwegian basins, five with and three without glaciers in the basin. Given the projected rise in temperatures, many Norwegian glaciers may disappear within the next 100 years (Oerlemans, 1997). By modifying the area of the glaciers expressed as the altitude of the front of the glacier, three alternatives were studied; front position and area as present, a front position corresponding to 50 % of the present area and a total removal of the glacier.

The summer runoff is projected to increase by 15–70 % in basins dominated by glaciers as a result of increased melting rate of the glacier ice. The annual flood peak may increase by 25–35 % in these basins. The summer runoff will decrease by 20–60 % in basins without glaciers in the same districts. Removing the glaciers totally from the basins will lead to a reduction in the summer streamflow in inland- and in northern Norway of 30–75 % compared to the present. West-facing basins in South Norway could expect a moderate increase in summer streamflow of 10–40 % compared to the present. Lack of glacial meltwater have less importance for the streamflow in the maritime parts of Norway, while removal of glaciers in inland and northern Norway will have profound effect of the streamflow.

The changes in the flood seasonality would be similar to those projected for glacier–free basins in West Norway when the glaciers disappear.

3.5 Conclusions

The natural variability of floods is so high that short term changes induced by climate change can be difficult to quantify. Provided that the climatic conditions since the middle 1980s would prevail, a number of conclusions about the near future can nevertheless be drawn. The recent years have mostly been warm, and the recent occurrence of floods is fairly similar to the flood regime of the 1930s, another warm period.

The large snowmelt floods in the major rivers, with high potential of flood damage to infrastructure on the flood plain is likely to be lower than in the earlier cooler climate, but large snowmelt floods can still occur as in 1934 and in 1995. The reservoirs and operation of the hydropower system has contributed significantly to reduce the risk of this type of floods. Earlier snowmelt, combined with rainfall can cause local flooding even in regulated rivers from the not regulated part of the basin. This kind of floods can become more of a problem in the years to come.

There will be more flooding especially in the lowland as a consequence of more warm events during the winter, although these floods will be substantially less than the spring floods of a cooler climate. These winter floods can result in more erosion of farmland. The shorter period of snow cover will lead to later floods in the early winter and earlier floods in the spring. Floods may therefore occur at times of the year, which now does not have floods.

The RegClim project indicates that rainfall events exceeding 50 mm a day will be more common along the west coast. Heavy precipitation events has not always caused severe flooding unless the initial conditions in the basins have been favourable or the precipitation has fallen as rain over most of the basin. If more of the heavy precipitation falls as rain as expected in a warmer climate, rainfall floods will be more common, and the severity will increase. Areas which has low annual rainfall such as the river valleys in the upper Glomma basin and the major rivers in Trøndelag draining northwards to the Trondheimfjord, will suffer from more flash flood events as seen in recent years, typically in the late summer, which also is the season when the rare weather type responsible for floods of the Storofsen type occur. Recently some high intensive events caused by remnants of tropical hurricanes have caused severe flooding at West Norway. Provided that the current activity of these storms continues, more severe flash floods can occur, typically in August–October in coastal basins in the west.

Increase in rainfall floods is more likely to cause damage in inland areas with low annual rainfall. Rainfall floods in areas with high annual rainfall are less prone to suffer damage, because the river channel is better adapted to cope with the higher runoff in these streams. An increase in rainfall intensities as indicated by RegClim will nevertheless increase the risk of flood damage also in these rivers.

Urban development will in combination with higher rainfall intensities lead to increased risk of damages to buildings and infrastructure. It is necessary to take this into account when dimensioning the urban drainage system including culverts. The risk of landslides has also to be taken into account when an area is considered for development.

The floods in glacier streams will increase as the glaciers are melting in a warmer climate. Less snow and firn will increase the albedo and the melting of the glaciers. This will result in increased peak floods as the retention capacity of melt water in the snow-pack is reduced. The flood regime will shift from summer floods to a spring flood regime in rivers as glaciers are disappearing in a previously glacierized. Thinning of glaciers in the front of glacier dammed lakes can trigger more *jökullhlaups* because of changes in sub-glacial rivers.

Historic and projected area changes in snow, weather, climate and water are shown on the internet site *http://seNorge.no*.

4 Expected changes in ice cover

(Randi Pytte Asvall and Ånund Sigurd Kvambekk, NVE)

Key points

- Only a few days shorter ice period in the most continental part of the country.
- The ice period decreases more towards the coast.
- Larger year to year differences.
- More ice runs which may jam at new places.
- Increased area along the coast with seldom ice.
- Longer reaches free of ice downstream large lakes.
- The lake ice will be thinner in the maritime regime, but less change in the area with continental regime.

4.1 Introduction

Information on ice cover has been collected in Norway for a long time. Ice runs have in the past caused substantial damage on the floodplain during winter flooding, with river bank failure as the most common occurring type of damage. Ice cover have also been utilised for transport purposes such as winter roads crossing lakes and inland rivers. Today the ice is less important for heavy transport, but still of importance for light-weight traffic and recreation. The importance of an ice cover for certain biological conditions has gradually been recognized.

4.2 Ice data

The information on amount and quality of ice varies with time and area. Information of past ice runs can be found in damage reports in the Norwegian Public Record Office (Riksarkivet) and in Kanalvæsenets Historie. Data from the instrumental period can be found in the older manual water gage observations, prior to the introduction of automatic recording instruments. The ice situation was observed every day, and we have many quite long series. These are mainly river stations. Water temperature measurements can supplement the river ice information in more recent years. The ice conditions and/or duration of the ice cover have been observed for many years in selected lakes.

Ice conditions for any year are a result of the weather of the corresponding winter, and not of the climate throughout previous year, as the case is for the biological life in a water course. Based on this we have selected years similar to typical years in the global warming scenarios for different parts of the country, and from there indicated a possible scenario for future ice conditions.

4.3 Winter climate in Norway

4.3.1 Present climate and simulated scenarios

The climate varies considerably from south to north and from coast to inland in Norway. The country is exposed to the warm Atlantic Ocean to the west causing fairly mild winters and heavy precipitation west of the main mountain ranges. The gradients in elevation are high from low coastland areas to high mountainous areas with narrow valleys with steep slopes, while wider valleys with moderate slopes are typical of areas east of the water divide. This causes large gradients and seasonal variations in climate, and consequently in runoff, snow and ice conditions.

Extensive work has been done to regionalize these data (Roald et al., 2006). Based on this work, regions for long-term variations in temperature, precipitation and runoff have been established. These parameters vary, and therefore also the outline and number of regions.

The changes in climate and runoff have been simulated for various scenarios. In evaluating the influence on ice cover we have used results from the HadAM3H-model with emission scenario B2 for the period 2071–2100 as compared with 1960–1990. There are significant seasonal differences in the projected changes. The conditions of the autumn, winter and spring seasons are important as regards the effects on ice cover.

The temperature is projected to increase for all seasons in all regions. The autumn temperatures are projected to increase throughout the country by 3.5–4° C, most in the northern inland (Finnmarksvidda). The winter and spring temperatures may increase by 2–3° C the south to 3–4° C in the far north, and also a gradient from 2–3° C from west to east.

The precipitation changes show a more even distribution throughout the country. The largest increases are in the autumn, being somewhat smaller in the winter and in the spring. Extreme precipitation events will occur more frequently, but the number of events with more than 20 mm/day will mainly increase at the western coast of southern Norway.

4.3.2 Streamflow

There are large variations for the different basins. Generally there is estimated a significant increase in streamflow in all regions for autumn and winter. For the spring there are only minor changes for the regions studied, except for the mountain plateau area in southern Norway. The short-time variations appear to increase, and along with more «extreme» weather, flooding situations caused by intensive rainfall are also expected to increase.

4.3.3 Duration of snow cover and winter freezing temperatures

The duration of ice cover is correlated with length of period with winter freezing temperatures and snow cover. Projected changes in snow conditions with data from the HadAM3 model run with the B2 emission has been studied (Schuler et al 2006).

Both the mean annual maximum snow water equivalent, and the duration of the snow cover season are expected to decrease almost everywhere in Norway. Generally the decrease gets smaller with increasing altitude, and distance from the coast. The start of the snow accumulation season is expected to occur approximately 3–4 weeks later than for the present climate in most areas. The snow melt season will start earlier, varying from 1–7 weeks, leading to an earlier end of the snow season.

The number of days with minimum temperature below freezing will decrease with 4 days in the inland north and inland higher areas in south, increasing to ca 20 days along the coast (Figure 4.1).

The seasons for ice cover and snow cover are not completely overlapping, as it may very well be ice cover on rivers and lakes before the time of permanent snow cover, or opposite.

On the average, however, a delay in start of the season for permanent snow cover will also give a delay in the start of the season for ice cover.

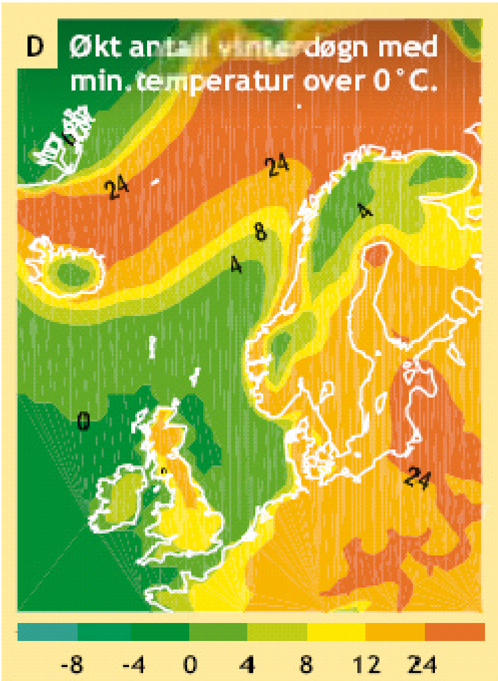


Figure 4.1 *Increased number of days with air temperatures above 0 °C both day and night (from Iversen et al 2005).*

4.4 Different ice-cover regimes

There are large variations in ice conditions throughout the country, and for different years, due to climatic variations. We have chosen three main ice cover regimes in this work (Figure 4.2):

- Continental regime
- Maritime regime
- Seldom ice regime

Continental regime: For regions with cold and stable winters the ice cover form in the fall, with thermal ice formation on lakes and slow flowing parts of rivers. On stretches with larger gradients there is dynamic ice formation, and after some time the ice conditions in the rivers stabilizes, and the ice on the lakes generally becomes safe for traffic. For locations where the water velocity is high, there will be thinner ice or open leads all winter. Winter ice runs do occur in the rivers, but rarely. However, the ice release in the spring will most often create an ice run.

Maritime regime : In more maritime areas, where the air temperature in the fall will experience a longer time of shifting between freezing and thawing, the ice cover will form and melt several times before a final winter ice cover may be established. Warm weather with rain and snowmelt will in addition occur any time in winter in these areas. This may initiate ice runs both in the autumn and winter, and cause ice

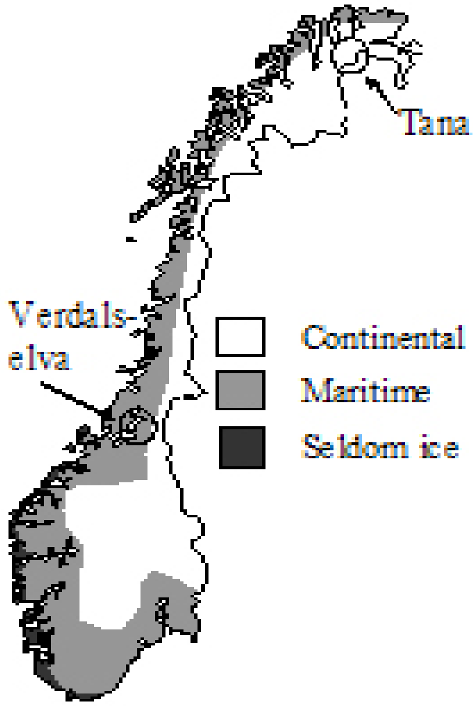


Figure 4.2 *Simplified map showing the three ice regimes and the two data sites.*

jamming and flooding. The lakes will have a shorter period with ice, and the ice will be generally weaker, and it tends often to be water on the ice.

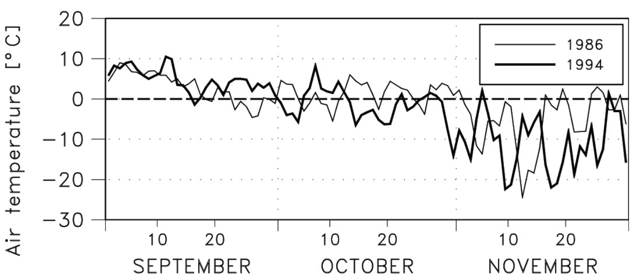
Seldom ice regime: Along the south-western coast the water temperature very rarely is lower than 0 °C, and there is normally no river or lake ice in the region. Downstream large deep lakes the water temperature is well above freezing all year, and these rivers thus have a seldom-ice regime. Deep large lakes in low altitudes also rarely get an ice cover.

4.5 Changes in ice cover regimes

For the north inland and central higher altitudes in south, which presently are dominated by a continental ice cover regime, the changes are predicted to be marginal. The average winter temperature is expected to increase, but only giving a few winter days more with temperatures above 0° C. This is due to the rather quick transition from summer temperatures well above zero to well below zero. Figure 4.3 shows this change for the inland in northern Norway (Finnmark). The weather changes from summer to winter within a month. The year 1994 is a year with average October temperatures, while 1986 has a monthly mean 3 degrees warmer than the average. The year 1986 can therefore indicate the future climate of 2071–2100.

Figure 4.4 shows the ice cover from the major river Tana in the same region. In the same figure are two thick lines indicating the time when the smoothed temperature passes zero in autumn and spring. It is easy to see the correlation between air temperatures and the ice covered period, and it is also striking that the variation from year to year is relatively small in the continental regime. In spite of 3 degrees warmer October in 1986 than in 1994, the onset of ice is fairly equal in time.

If, however, the conditions of extreme weather situations increase, one might expect more cases of



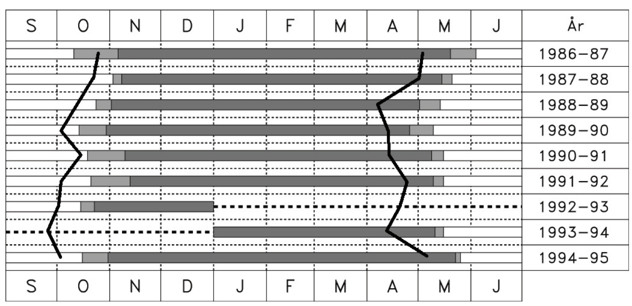
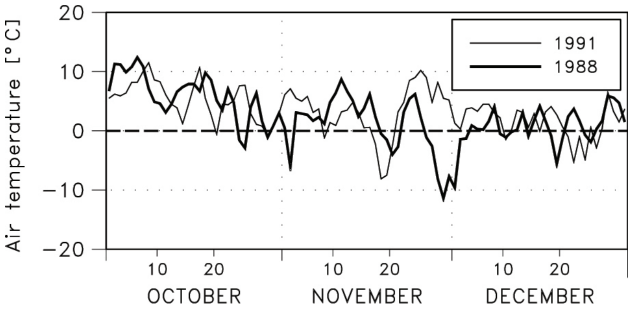


Figure 4.3 *Air temperatures from Karasjok in the northern inland of Norway from September to November. See upper circle mark in Figure 4.2. The year 1994 is a year with average October temperatures, while 1986 has a monthly mean 3 degrees warmer than the average, indicating the future climate of 2071–2100.*

Figure 4.4 *Ice cover in the river Tana (inland northern Norway, upper circle mark in Figure 4.2). Light shading indicates partly covered and dark shading indicates completely ice covered river. The dates where the smoothed air temperatures at the nearby station Karasjok passes zero, are indicated with thick lines in the autumn and in the spring. (---- indicates missing data.)*



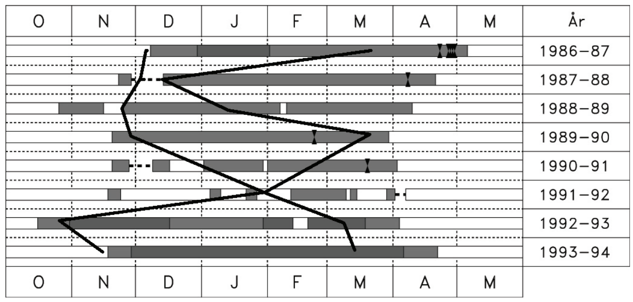


Figure 4.5 *Air temperatures from October to December at Værnes in the maritime regime. See lower circle mark in Figure 4.2. The year 1988 is a year with close to average November and December temperatures, while 1991 has a monthly means 2.5 degrees warmer than the average, indicating the future climate of 2071–2100.*

Figure 4.6 *Ice cover in the river Verdalselva (maritime regime). See lower circle mark in Figure 4.2. Light shading indicates partly covered and dark shading indicates completely ice covered river. The dates where the smoothed air temperatures at the nearby station Værnes passes zero (if any), are indicated with thick lines in the autumn and in the spring.*

ice runs and jamming of ice. This is not likely to affect the northern inland, but may be of significance in the southern inland areas.

For the rest of the country, with maritime ice cover regimes, the ice cover season will be shorter. The year 1991 indicates the future climate for the maritime regime (Figure 4.5). There was very little ice that year compared with more years with average temperatures, as in 1986. The weather changes frequently between warm and cold periods, and the smoothed temperature is not as well correlated with ice onset and offset (Figure 4.6) as in the continental regime. We also expect greater year to year variations in the ice cover in those part of the maritime regime that are fairly stable today. More extreme weather will, also here, initiate more ice runs. The location of the release points for the ice runs may, however, be located higher up in the rivers. This implies that ice jamming might occur on new places, challenging the settlements along the rivers.

The extent of areas with seldom ice will increase. Figure 4.7 is based on the mean air temperature in January. The dark areas have temperatures above the freezing point and indicate areas where ice is seldom in the rivers and the lakes today. The grey area is calculated from the above referred scenarios for 2071–2100 where the temperature along the coast increases approximately 3.0 °C in the most northern part (Troms and Finnmark), and 2.5 °C in the rest of the country.

The climate simulations indicate only a small increase in the wind. The air temperature increase is therefore the most important factor. The previous described impacts of the climatic change are therefore valid both for lake ice and river ice.

The lakes will be warmer, especially in the start of the ice season, so the rivers downstream of large lakes will get a longer stretch with no ice or weakened ice.

Due to the insulation of snow and ice cover, the ice thickness is only increasing slowly in the last part of the winter in the continental regime. In the maritime regime the ice is thinner, or the snow wetter, both giving less insulation. A cold period will therefore give a significant increase in the ice thickness. There will be fewer cold periods in the future climate, and hence significantly thinner ice in the maritime regions.

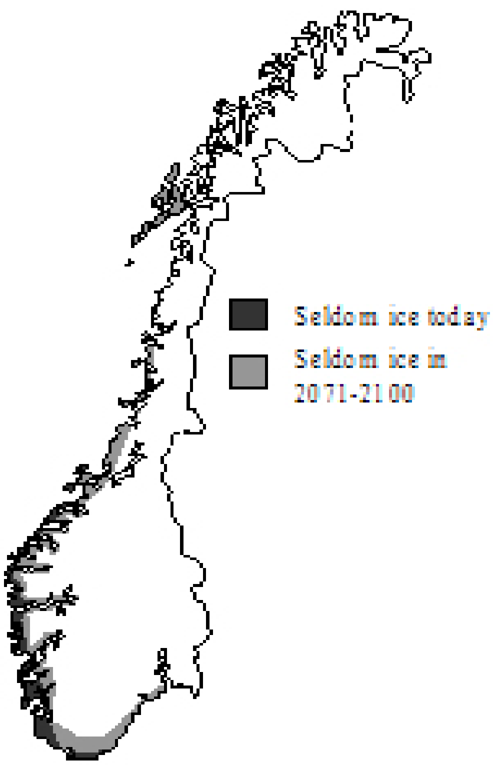


Figure 4.7 *Areas with seldom ice today and in the future climate of 2071–2100.*

4.6 Conclusions

Future climate in Norway, based on the results from the HadAM3-model, is expected to give a warmer winter climate all over the country. The major impacts on the ice cover in rivers and lakes are:

The length of the ice season is particularly sensitive to length of time with freezing temperatures and amount of snow fall. Mild spells and heavy rainfall in the winter can trigger ice jamming and ice runs when ice cover has developed. The downscaled scenarios of global warming indicate that the projected changes in temperature will differ regionally in Norway. More unstable ice conditions are expected along the coast and maritime areas from the south and as far north as to the arctic circle. The effect on ice will be somewhat different on rivers than on lakes.

The areas where the ice runs and jamming starts will shift to higher altitudes, moving the maritime ice cover further inland. This can cause a possibility of damages at other settlements than those suffering from ice runs in the past. The season with the risk of ice runs will be shorter, but the year to year variability will be high. Extreme winter rainfall events after the ice has formed can cause severe ice runs.

5 Changes in frequencies of high wind speeds

(Rasmus Benestad, Eirik J. Førland and Knut Harstveit, met.no)

Key points

- There are pronounced inter-annual and inter-decadal variations in the observed frequencies of wind speeds exceeding the threshold value for strong gales.
- Analysis of observed wind series from coastal regions in Norway do not show any evident trend in the frequency of strong winds from 1961 to 2006.
- For a longer time-scale, analysis of estimated geostrophic wind does not indicate any significant changes in wind speeds in Norway and adjacent sea areas since 1880.
- Scenarios for future wind conditions do not indicate any clear tendencies for changes during the next 50–100 years, although several studies indicate that the most intense mid-latitude storms may become more frequent in a warmer climate.

5.1 Observed changes in frequencies of wind force ≥9 Beaufort (strong gale)

(Rasmus Benestad, Knut Harstveit and Eirik J. Førland, met.no)

There are few long homogeneous series of measured wind speed in Norway. Figure 5.1 is based on data from four stations in each of three Norwegian regions; i.e. coastal regions in South-eastern, Western and Northern Norway (K.Harstveit, pers.comm). The figure indicates that the frequency of wind force ≥9 Beaufort (B), i.e. equal to or stronger than strong gale seem to have decreased in South-eastern Norway during 1960–2002, while Northern Norway has a period around 1990 with 50 % more days with winds ≥ 9B than the average value for the period 1961–90. In Western Norway and on average over the whole country, a tendency to increasing frequencies of strong winds seems to be broken by a falling tendency during the latest years. The main conclusion from this analysis is that the wind series from coastal regions in Norway do not show any evident trend in the frequency of strong winds from 1961 to 2006.

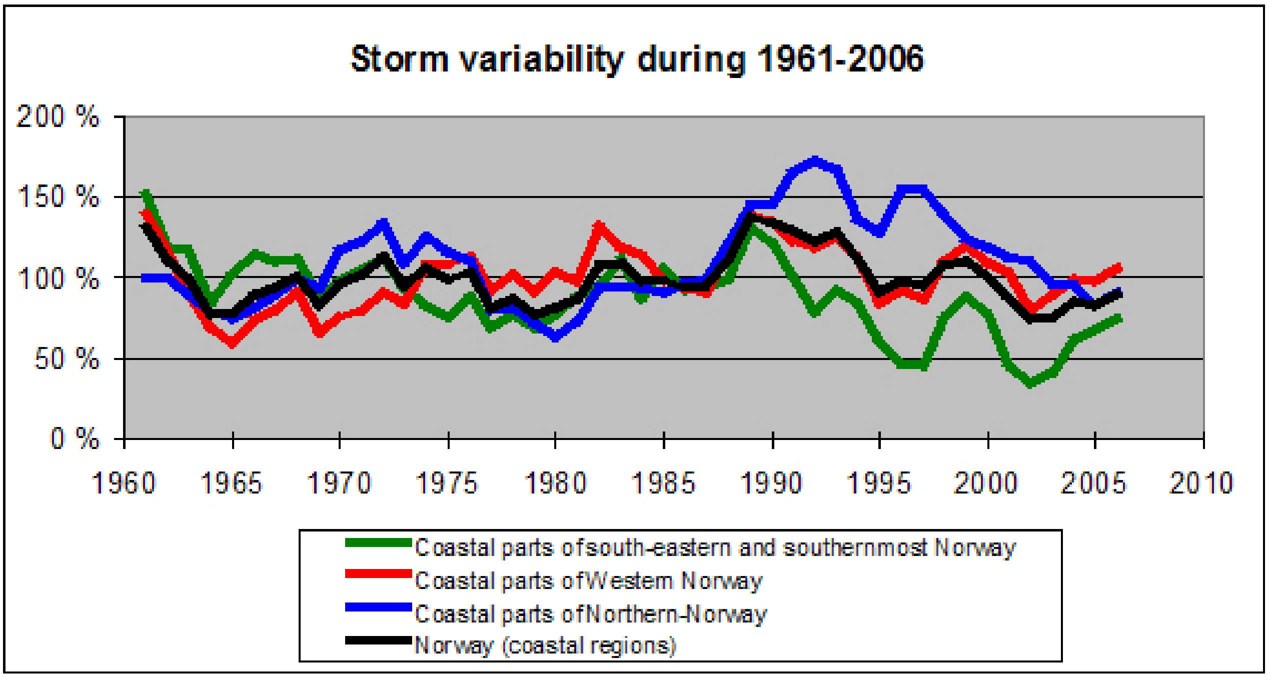


Figure 5.1 *Number of days with wind force ≥ 9B (strong gale) during 1961–2006 as percentage of the mean value for the normal period 1961–90. Because of the large inter-annual variability, the graphs are presented as 3 years running means.*

Because of the lack of long, homogeneous series of measured wind speed, «geostrophic wind» is often used as an indictor for changes in wind conditions. Geostrophic wind is estimated from atmospheric air pressure values reduced to sea level. In a study of long-term changes in geostrophic winds over Northern Europe, Alexandersson et al (1998, 2000) concluded that over the North Sea and Norwegian Sea there was a high frequency of storms during the period 1881–1910, but that the frequency generally decreased up to ca. 1965 (see Figure 5.2). From 1965 the frequency increased up to around year 1990, when the frequency was at about the same level as 100 years earlier. Alexandersson et al (2000) concluded that «the 1880s still appear as the most prominent storm decade during the 120 years of high-quality observations of air pressure». It should be noted that the last part of the graph in Figure 5.2 is quite consistent with the main features of Figure 5.1. The main conclusion is that there has not been any significant trend in frequency of wind force ≥9B in the Norwegian ocean or coastal areas since 1880.

Also Yan et al. (2006) found a tendency to increasing wind speeds over the ocean areas in the North Atlantic / North Sea during the period 1958–1998, particularly in the winter season. An analysis of cyclone tracks by Benestad & Chen (2006) indicates that there has been an increase in the occurrence of strong cyclones

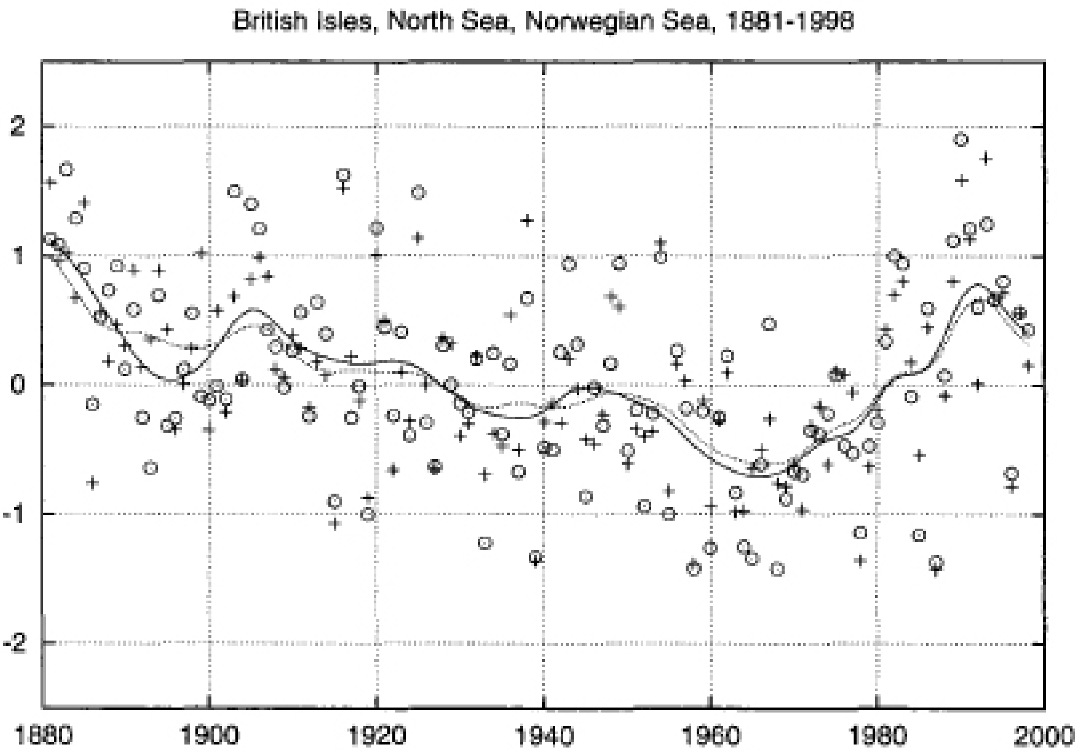


Figure 5.2 *Average of standardised 95 (+) and 99 (○) percentiles and corresponding smoothed curves (solid and dotted lines respectively), 1881 to 1998 for the British Isles, North Sea and Norwegian Sea (from Alexandersson et al., 2000).*

over the Northern Europe during the latest 40 years, and a reduction over the European Continent. The frequency of strong winds and number of cyclones passing our region are connected to the force of the westerlies over the North Atlantic. The force of these westerlies is linked to the so-called North Atlantic Oscillation; often referred to as «NAO».

Another approach is to analyse pressure gradients, through geostrophical wind analysis, for places where long time series of sea level pressure exist. The geostrophic wind is estmated from the sea level pressure between three different locations (a triangle). Such an analysis for historical measurements can be used as the basis for return value analysis (Figure 5.3), and the results suggest different long-term changes for northern and southern Norway. In the south, the geostrophic wind speed has become weaker whereas the opposite trend can be discerned in the north. This patterns in consistent with the interpretation of a northward shift of the storm track. Yan et al. (2006) adopted a different approach and inferred a tendency of increasing wind speeds over the northern seas for the interval 1958–1998, and in particular for the winter season. Frequent recurrence of high wind speed can be explained in terms of a high NAO index. These observations also are consistent with the conclusions of Benestad & Chen (2006). Pryor et al. (2005, 2006) applied empirical downscaling techniques to the wind speed distribution (assuming Weibull) and various climate scenarios, and estimated small (insignificant) changes (<15 %). The geostrophic wind analysis from several RCMs are compared with similar analysis based on historical sea level pressure records in Figure 5.4. Common for all the model results is that they yield lower wind speed in the geostrophical wind analysis, and there is a weak bias in the north-south component (southerly winds are too weak). A close inspection of the various geostrophic wind speed distributions suggest that there are small differences between the control and scenario runs as well as between models, in line with the results from Pryor et al. (2005, 2006). The various models also indicate different changes in the extreme winds, as the met.no HIRHAM/HadCM3 projects a small increase in the extreme wind speeds whereas the SMHI RCM suggests weakening in the extreme values. The historical data, on the other hand, exhibit more substantial changes, in line with Yan et al. (2006). Historically, there have been pronounced variations in the geostrophic wind speed from time to time, while the models only describe marginal differences. Additionally, the climate models have systematic errors in the description of the geostrophic

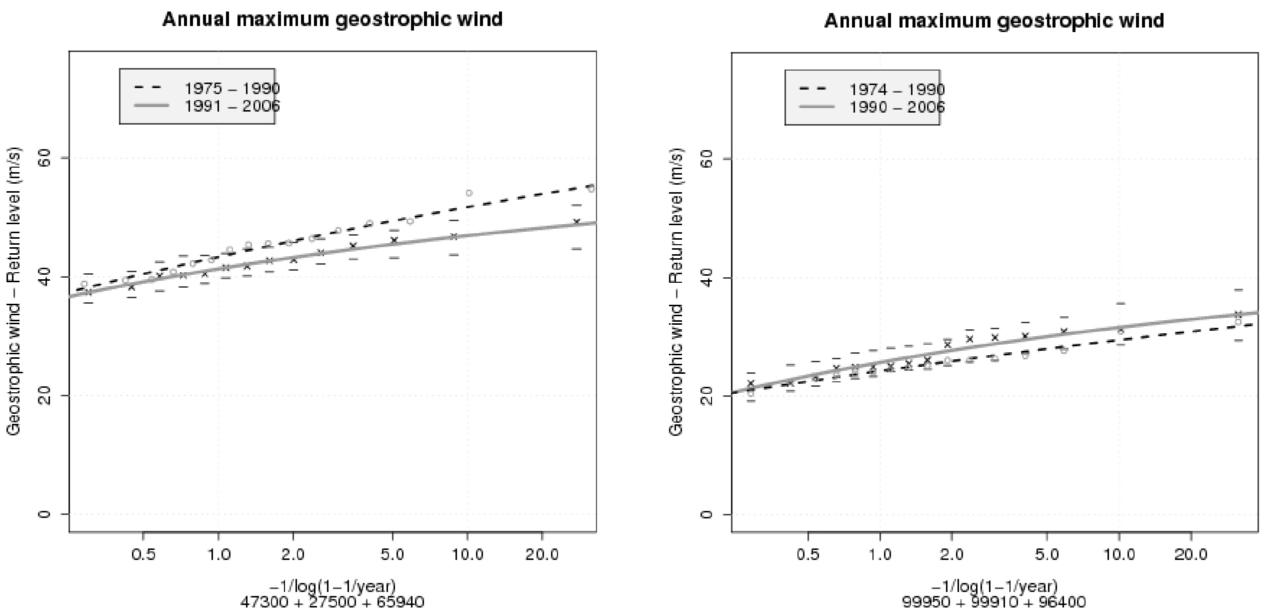


Figure 5.3 *Extreme value analysis of geostrophical winds estimated for two different triangles based on historical measurements from*
a) Southern Norway (27500 Færder – 47300 Utsira – 65940 Sula)
b) Northern Norway and Norwegian Sea (96400 Slettnes – 99910 Ny-Ålesund – 99950 Jan Mayen)

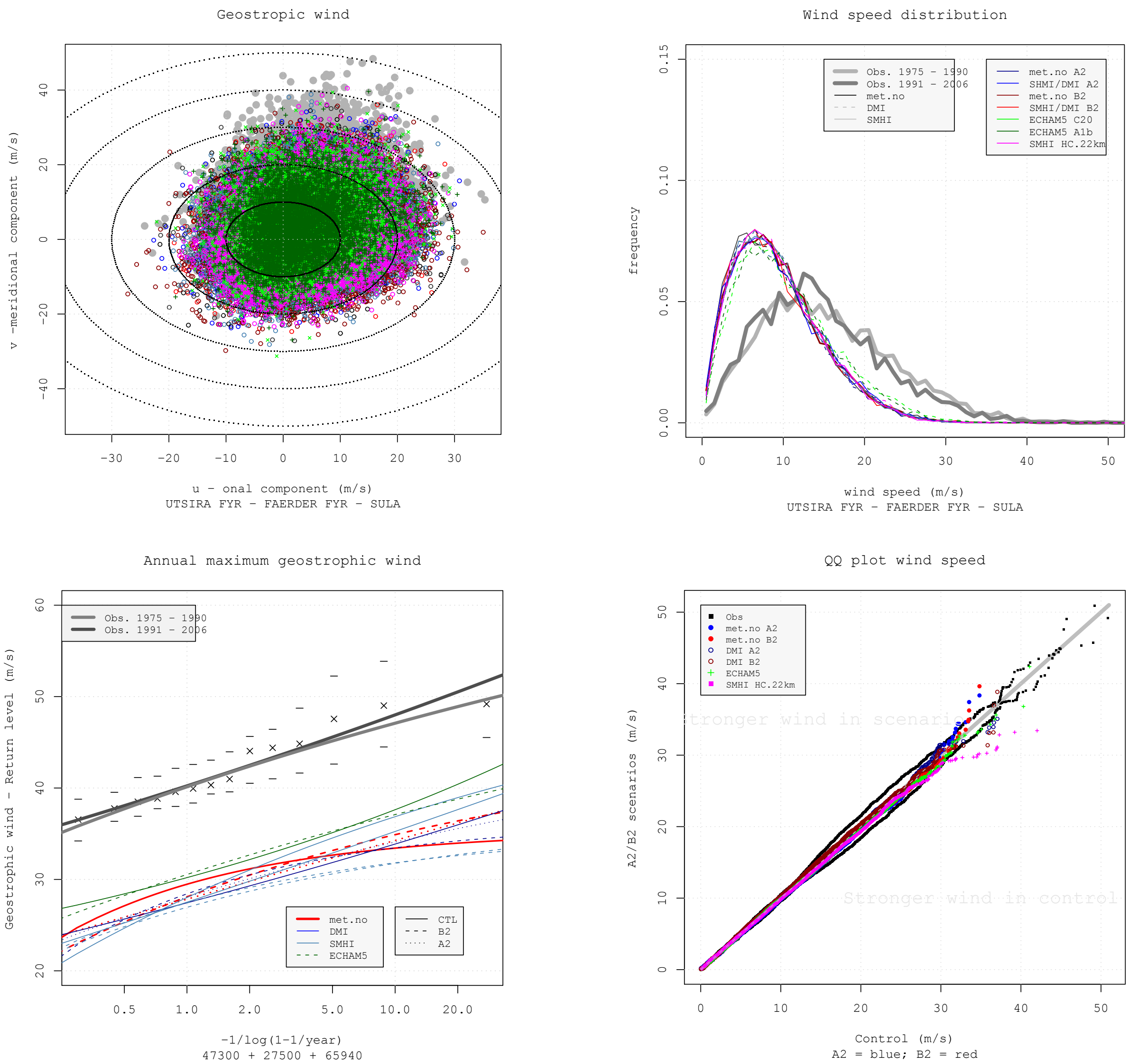


Figure 5.4 *Geostrophic wind analysis for various RCMs/GCMs (CTL and scenarios) estimated for a triangle over southern Norway. (a): scatter of the north–south and east–west wind components (positive values: west-to-east, and south-to-north); (b) distribution of wind speeds; (c) return-value analysis; and (d) quantile-quantile plots.*

wind (sea level pressure pattern). These discrepancies may suggest that the models will under-estimate any future change in wind speeds. However, the analysis of the directly measured winds (Figures 5.10–5.13), on the other hand, suggest weaker variations in the wind speed. Geostrophic wind analysis is usually regarded as the more reliable approach for studying long-term changes in the wind speeds.

5.2 Scenarios for changes in extreme wind conditions

(Rasmus Benestad, met.no)

Scenarios for changes in wind speed are more uncertain than for most other climate elements. A common feature is that geostrophic wind based on the air pressure fields in the climate models do not reproduce a proper distribution of the real wind speeds and also have a tendency to under-estimate the wind speed as well as the changes in wind speed. Thus it is rather difficult to estimate changes in occurrences of wind speeds exceeding a given threshold value e.g. > 20.8 m/s (strong gale). The projections in Figure 5.5 indicate rather small changes in the frequency of high wind speed up to the period 2071–2100. Analyses at met.no and a study from Germany (Leckebusch et al., 2006) show that different climate models give different answers: Some indicate an increase in the storm activity while others indicate reduced storm activity over our Northern Europe. However, Leckebusch et al. (2006) conclude that the strongest storms will be more frequent in the future. This conclusion is not supported by Bengtsson et al (2006) on a global scale. Both Bengtsson et al (2006) and Yin (2005) argue that the storm tracks will move northwards under a global warming. Such a change will have more serious local consequences than changes in global number of storms. Bengtsson et al (2006) estimates an increase in frequency and intensity of storms during the winter season in parts of Southern Norway, as well as an increase in storm activity in parts of the Arctic during the summer season.

Pryor et al. (2005, 2006) performed empirical downscaling of the distribution of wind speeds for various scenarios, and found just small changes for Northern-Europe and adjacent ocean areas. Based on analyses of several climate models, Benestad (2005) found no evident indications of neither more nor less cyclone activity over our areas.

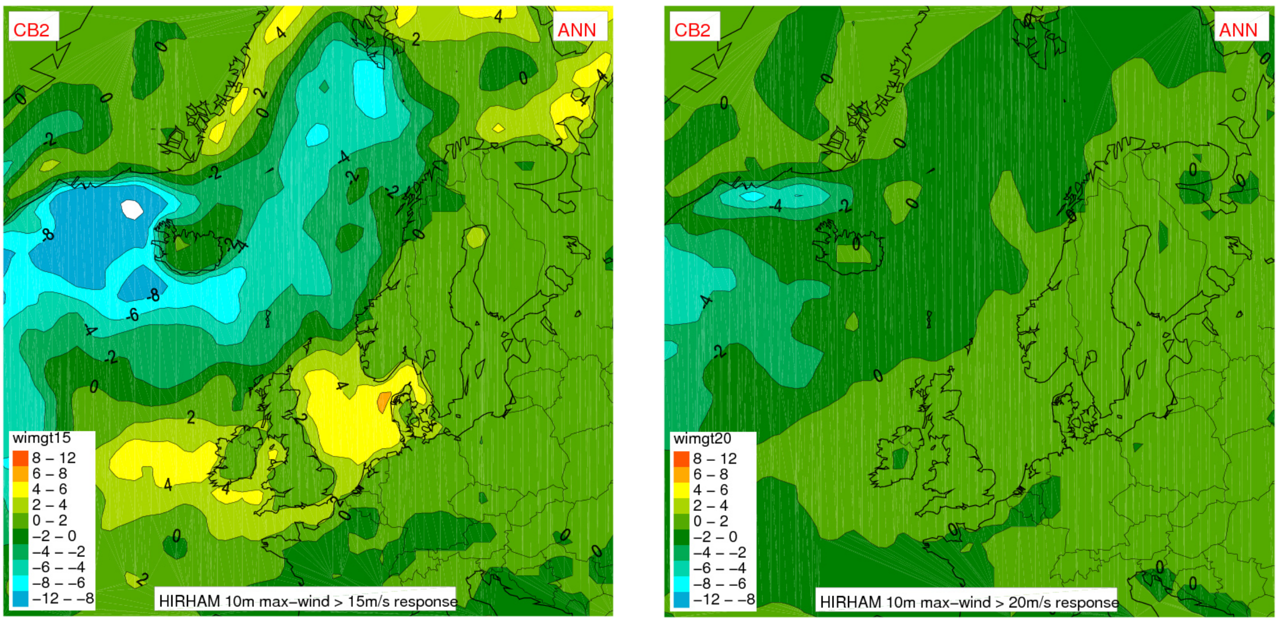


Figure 5.5 *Changes in number of days per year wind speed exceeding resp. fresh gale (8B, left) and strong gale (9B, right). The figures are based on combined data from the Hadley and MPI-models with emission scenario B2, and show projected changes from the period 1961–90 to the period 2071–2100.*

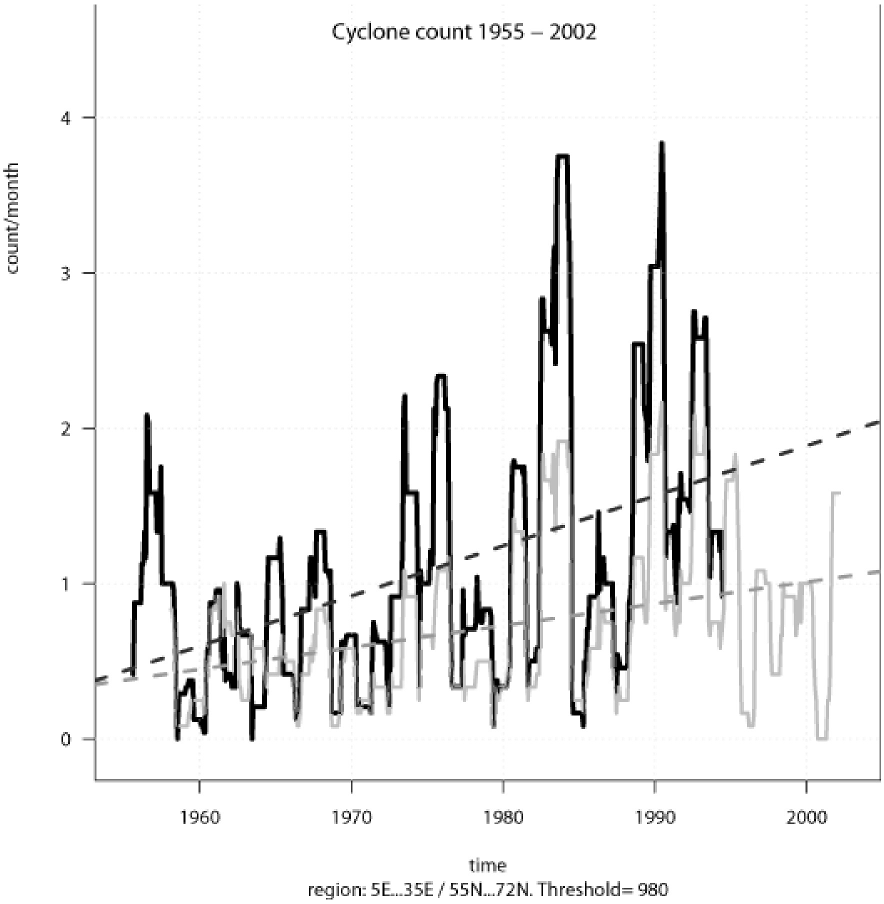


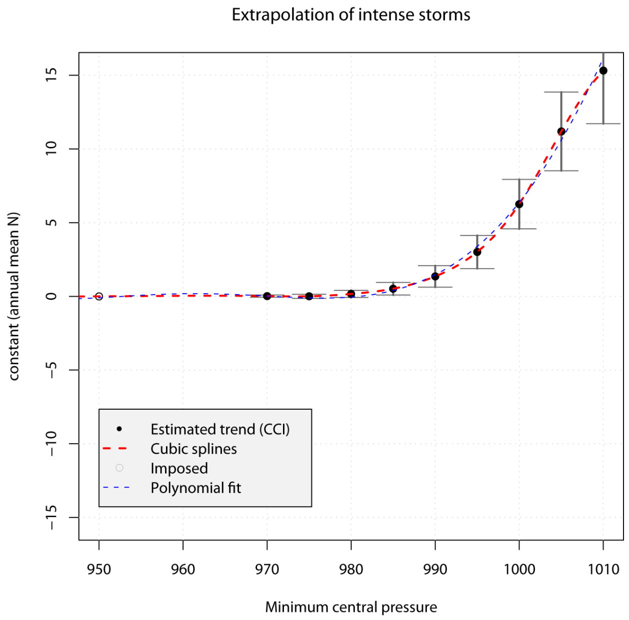
Figure 5.6 *Time series showing the time evolution of the number of low-pressure systems with central pressure lower than 980 hPa in the region 5 ºE – 35 ºE / 55 ºN – 72 ºN analysed from the ERA40 (grey) and NMC (black) gridded sea level pressure data.*

5.3 Novel analyses of high wind speeds and cyclone frequencies

(Rasmus Benestad, met.no)

Storms are often associated with strong winds («eg. The New Year storm of 1992: «Nyttårsstormen 1992»), but such storms may also result in heavy precipitation (eg. The residues of «Hurricane Maria» Sept. 14, 2005). Changes in the storm tracks, as for instance their position, may have greater influence locally on the storm frequency than the total global number. If the storm tracks are shifted poleward as a result of a global warming, this may influence Northern Norway severely even if there is no change in the number of storms globally. Analyses of historical storms suggest that the North Atlantic storm track may have been displaced northward during the recent decades, with fewer storms over the continental Europe and more storms over Scandinavia and Iceland. Yin (2005) analyzed 15 GCMs and identified changes in wind and precipitation consistent with a poleward shift in the storms tracks. His analysis also gave indications suggesting that a global warming may bring more intense storms.

An analysis of projected storm statistics was carried out at met.no based on the sea level pressure of the cyclone centres, but this analysis did not give any clear indication of increased storm activity (more frequent or stronger storms) in the Nordic region for the future. The central cyclone pressure gives an indication about the storms' strength (the lower the pressure, the stronger the storm), but it is also possible to estimate the wind speed associated with the spatial pressure gradients. Trend analysis based on the central storm pressure for the past suggest that there has been an increase in the storm activity for the period 1955–2002 for storms with a central pressure lower than 980 hPa. Such trend analyses become increasingly uncertain with the storm severity. It may nevertheless be possible to utilize the information about trends of more frequent and less severe storms for the extrapolation to the more extreme cases if it is assumed that the magnitude of the trend changes slowly and smoothly with the storm strength and



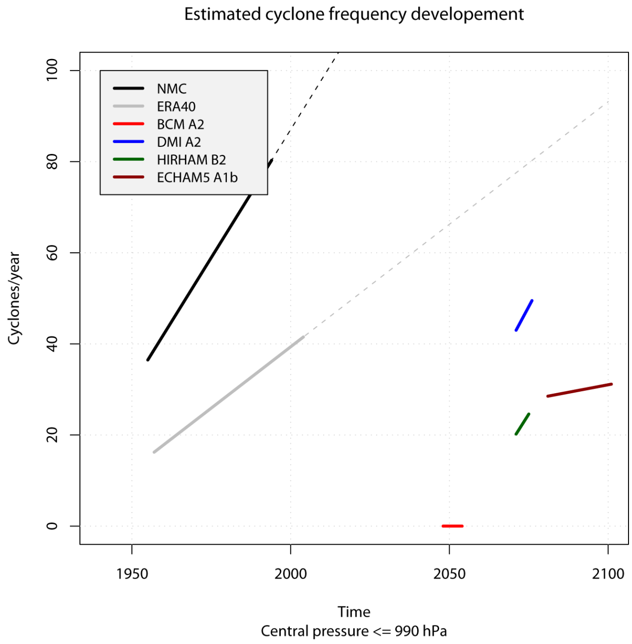
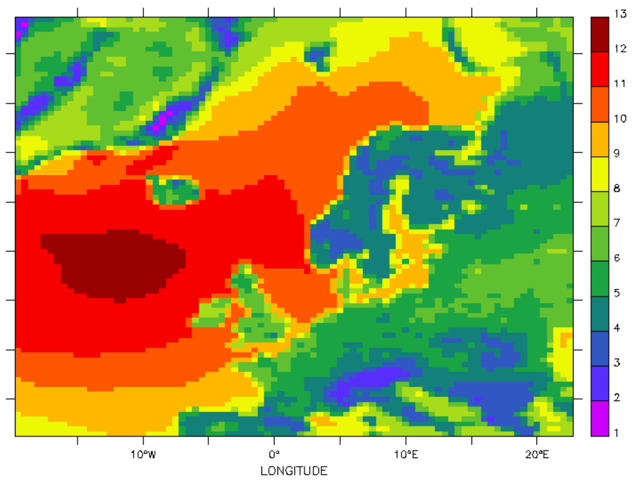


Figure 5.7 *Left: function showing how the trend magnitude varies with the central pressure of the storms. Right: estimates of the storm frequency based on rCM results as well as observed trends (ERA40 & NMC).*



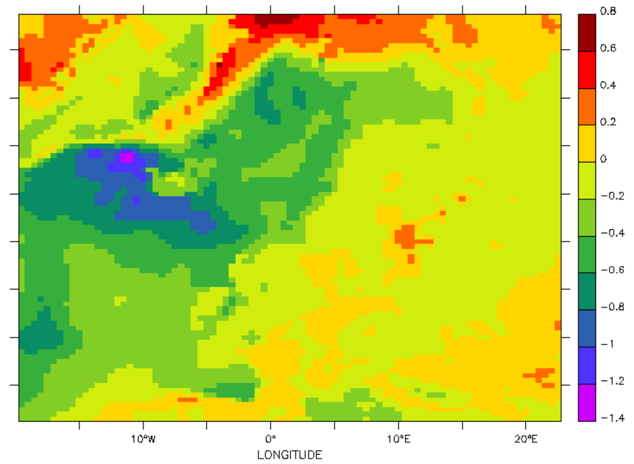


Figure 5.8 *Present-day control results and change in maximum 10 m wind speed. HIRHAM/HadCM3, 2070–2100.*

that the trends converge to zero for very low central pressures (Figure 5.7). Such an exercise has been done for the historic trends, but similar analysis for the projected trends do not give any clear indications of increases for the future, but these results are still uncertain as these so far are based on a small data sample.

Bengtsson et al. (2006) analysed storm statistics in the ECHAM5 model and validated the model represenation of cyclones against the ERA40 renalysis. They found no indication for more intense storms as a result of a global warming (SRES A1b scenario), but inferred changes in local patterns of storm statistics. In general, the storm tracks exhibited a northward shift, but a reduction was found in the winter (DJF) storm track density and mean intensity for northern Norway. For southern most part of Norway, on the other hand, the model indicated an increase the intensity and possibly also in the track density. For the summer season (JJA), the model suggested an increase in the mean intensity over northern Norway and large parts of the Arctic, but this feature was not seen in the track density.

Storms can be represented more accurately in RCMs with higher spatial resolution than in GCMs. But it is not clear whether the RCMs give a better representation, as the KNMI '06 scenarios (van den Hurk et al., 2006) report that low-pressure systems in an RCM may not be any deeper than in the more coarse GCM used to provide the boundary conditions. Thus, a misrepresentation of the low-pressure systems may be sensitive to how the models studies are designed, and a model study from the European

Centre for Medium-range Weather Forecasts (ECMWF) suggested that the number of low-pressure systems and their intensity is sensitive to the global models' spatial resolution (based on a different model to the KNMI scenarios). RCMs also tend to suggest only minor changes in the wind speed (Figure 5.8). Different GCMs have have different strengths and weaknesses associated with describing the climate, but wind is one parameter which is in general not well-described by the models as for instance pressure and temperature. The raw historical wind speed measurements often suffer from errors as well as low quality (Figure 5.9), and it is therefore necessary to apply a quality control before use. Figure 5.10 shows time series of annual maximum wind speed, based on quality control and consultations from Knut Harstveit (pers. comm.).

A typical characteristic for the wind speeds is the pronounced interannual variation. There is no clear trend in the data shown in Figure 5.10, but there are great geographical differences. Figure 5.11 shows the return-value analysis, based on an extreme value distribution, for Oslo (18700) and Ørland (71550), indicating that wind speeds exceeding 20.8 m/s rarely occurs in Oslo, whereas such values are more commonplace in Ørland. Figure 5.12 shows two distributions for the annual maximum wind speeds for all the locations, one for the first 15 years and the other for the last 15 years. Despite differences in details, there is no clear systematical difference between the two distributions.

A record-value analysis (Figure 5.13) can be used to assess whether the upper tail of the distribution has been stretched towards higher values over time. Such an analysis can be applied 'forward in time' as well as 'backwards', and a shift in the tail is higher number of record-breaking events than expected from an independent and identically distributed variable (iid) and lower number of record-breaking cases for the backward analysis. The results obtained here, to the contrary, suggested slight indications of higher number of record-events for the backward analysis, which is consistent with a weakening of the maximum wind speeds. However, if the wind speed has a year-to-year dependency (serial correlation), this may influence the results.

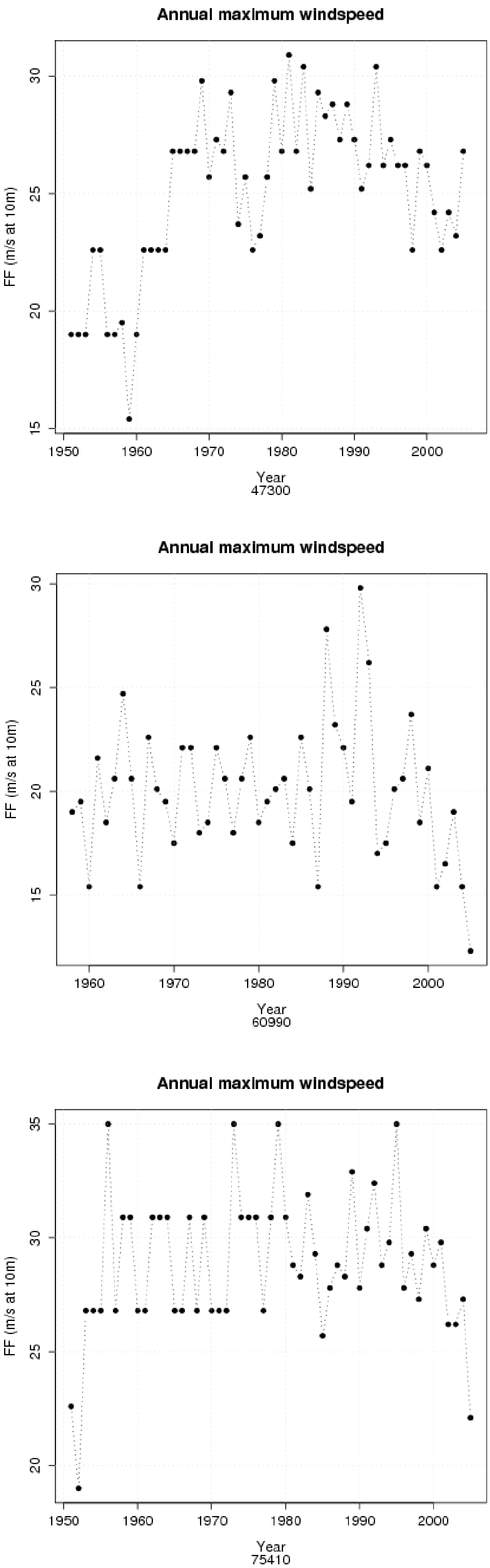


Figure 5.9 *Examples showing annual maximum wind speed from 3 locations in Norway. At some locations and some periods, the wind speed data is of poor quality (a-b). If the quality information is not given, then it is hard to say wether changes in the characteristics are real or due to erros (c).*

In addition to using series of measured wind speeds from traditional wind meters, it is in principle possible to use Doppler radar measurements. Such radar observations are fairly new and do not go sufficiently back in time to allow a good statistical sample for extreme value analysis.

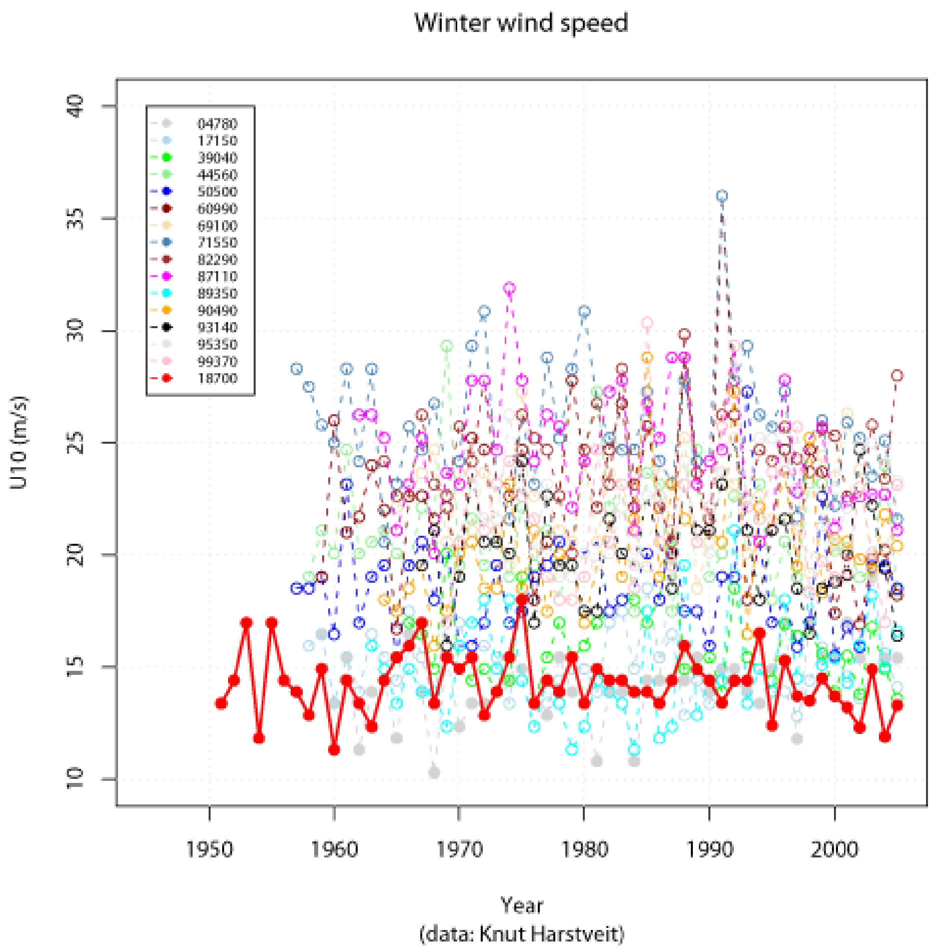


Figure 5.10 *Time series for maximum wind speed from quality controlled records (data from Knut Harstveit).*

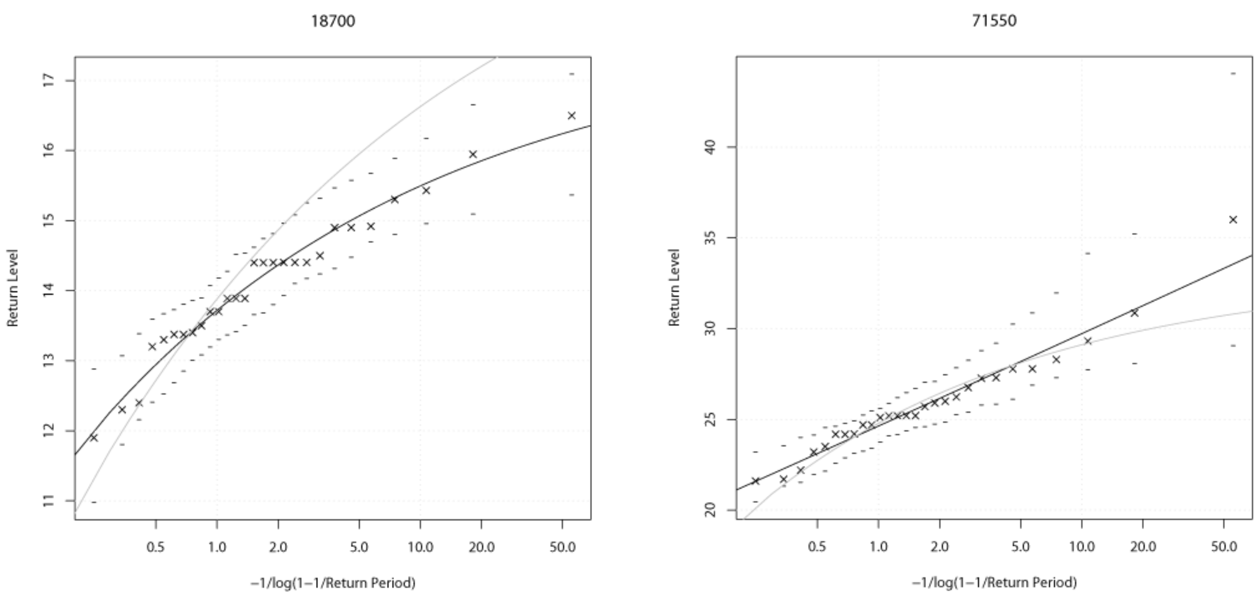


Figure 5.11 *Extreme value distributions and return-value analysis for Oslo (left) and Ørland (right) (data from Knut Harstveit).*

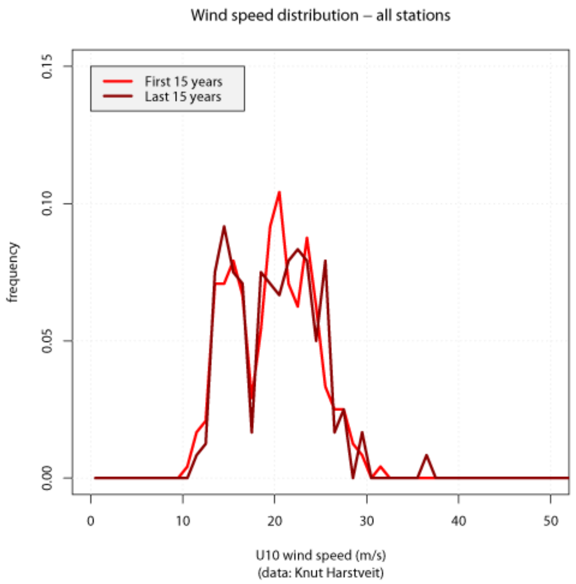


Fig. 5.12 *Distribution of aggregated wind speed statistics for norway for two periods with the same number of observations in each (data from Knut Harstveit).*

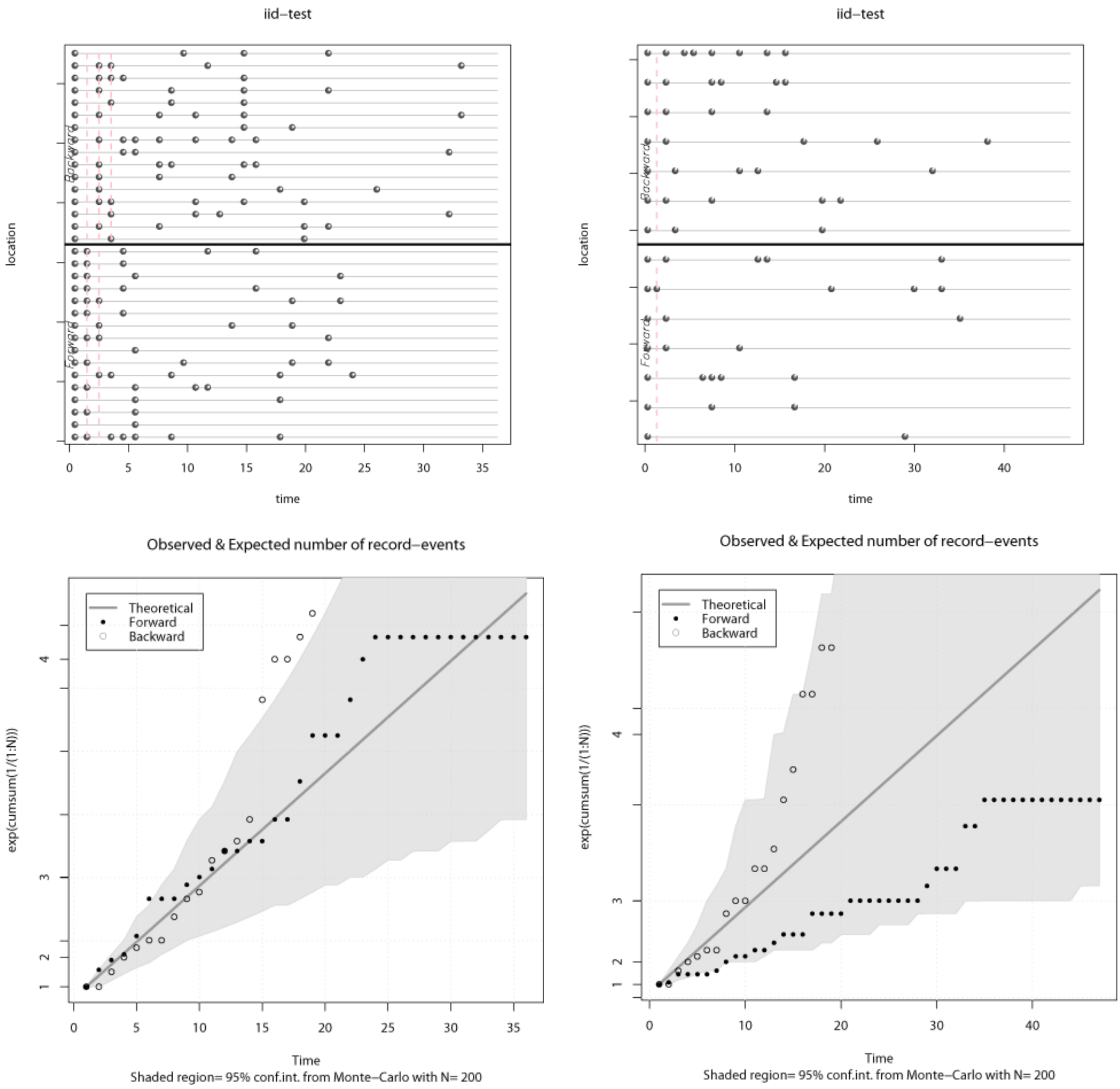


Figure 5.13 *Record-value analysis for the annual maximum wind speed (data from Knut Harstveit). The upper panels show the timing of new record-breaking events for forward as well as backward analysis, whereas the lower panels show the average number of record-events as a function of time. Left: the analysis for a few long series; right: the analysis for many shorter series.*

6 Changes in sea level and frequencies of storm surges

(Joe LaCasce and Jens Debernard, met.no)

Key points

- Results from IPCC TAR suggested that the sea level height could rise between 0.025 and 0.25 m along the Norwegian coast over the next 50 years.
- More recent studies, which take into account increased melt water run-off from the Greenland and Antarctic Ice Shelves, suggest that the rise could be twice as large, or up to 0.5 m.
- The mean rise sea level rise will be ameliorated by continental uplift in Scandinavia, which will raise the Norwegian coasts by 0.05–0.25 m.
- Thus it is conceivable that there will be no net change in mean sea level height (SLH) at some locations along the Norwegian coast in the next 50 years. But if the mean SLH rise is large as 0.5 m, significant increases in SLH will be evident at all locations.
- The projections up to 2050 do not exhibit a significant change in the probability distributions of sea level height along the Norwegian coast. This implies that the standard deviations and the frequency of extreme events will not change significantly. The evidence for more frequent storm surges is therefore weak, in the absence of mean sea level rise.

6.1 Changes in sea level

Climate change could affect the sea level along the Norwegian coast in two primary ways. First, the warming of the ocean and the melting of the large ice sheets could increase the mean sea level height. So low-lying coastal regions could find themselves under water, and tides will be correspondingly higher. But in addition, changes in the paths and intensities of storms could alter the frequency of storm surges. So coastal flooding could become more common.

We will address these two issues in turn. First we examine the short term variability using numerical ocean simulations under various climate scenarios. Such variability reflects tidal excursions as well as extreme events (storm surges). The simulations involve projections of oceanic conditions 30–100 years hence, in the absence of a mean shift in sea level.

Then we consider possible changes in the mean sea level height, by reviewing projections from the 2001a IPCC report and from recently published literature. These analyses reflect what changes we are likely to see over the next 50–100 years, and put those changes in the context of measured changes over the past 20,000 years.

6.2 SLH Variability, Storm surges

6.2.1 Model simulations

We first examine projections of sea level height (SLH) variability, assuming different climatic conditions. The latter derive from numerical ocean simulations run in Norway under the RegClim program. The simulations were «dynamically downscaled», meaning they used input from a coarse resolution global climate model to drive a high resolution atmospheric climate model for the Nordic region (called «HIRHAM»). Two different global climate models were used, one from the Max Planck Institute in Germany and one from the Hadley Centre in the U.K.

The high resolution simulations produce downscaled scenarios for wind and sea level pressure. These were then used as input for a regional storm surge model. The latter was essentially identical to the model used for operational storm surge forecasts at the Norwegian Meteorological Institute (Engedahl, 1995). It predicts weather- and tide-induced variations in SLH.

The main difference between the various simulations is in the global model used and in the choice of greenhouse gas scenario. From the Max-Planck Institute (MPI), we have used two different simulations. One is the MPI-GSDIO simulation, based on the IPCC IS92a greenhouse gas scenario. The downscale methods and MPI-GSDIO scenario is discussed in more detail in Debernard et al. (2002). From this simulation, the downscale periods were taken as two 20 year long time slices. The first period, covering 1980–2000, is considered as the control period and the second, covering 2030–2050, the scenario period. The difference between these is thus indicative of the changes one would expect in the next 50 years, under this IPCC gas scenario.

The other simulation from MPI is the SRES B2 scenario, where two 30-year time-slice periods, from 1961–1990 and from 2071–2100, are taken as the control and scenario, respectively. From the Hadley Centre (HC) we have used two different SRES greenhouse gas scenarios (A2 and B2). In these, the 30-year periods are the same as in the B2 scenario from MPI. The three last scenarios (MPI-B2, HC-A2, HC-B2) were analysed and discussed by Røed and Debernard (2005).

6.2.2 Results

We will focus on the MPI-GSDIO simulations, as these results are indicative of the rest. Shown in Figure 6.1 are bi-histograms of SLH from six locations along the Norwegian coast. These were constructed from hourly SLH data, with tidal deviations included.[1] Each histogram (or probability density function; PDF) was normalized by the total number of realizations, so that the value on the y-axis indicates the frequency of occurrence. The x-axis corresponds to actual heights (the heights themselves were not normalized). The lower curves correspond to the period 1980–1999 and the upper curves to the period 2030–2049. The corresponding standard deviations are indicated in left hand corners of the plots.

1) One can also examine the SLH deviations with the tides removed, as in Debernard et al., (2002). We have chosen to focus instead on the total SLH field, as this is what is relevant to land-based observers.

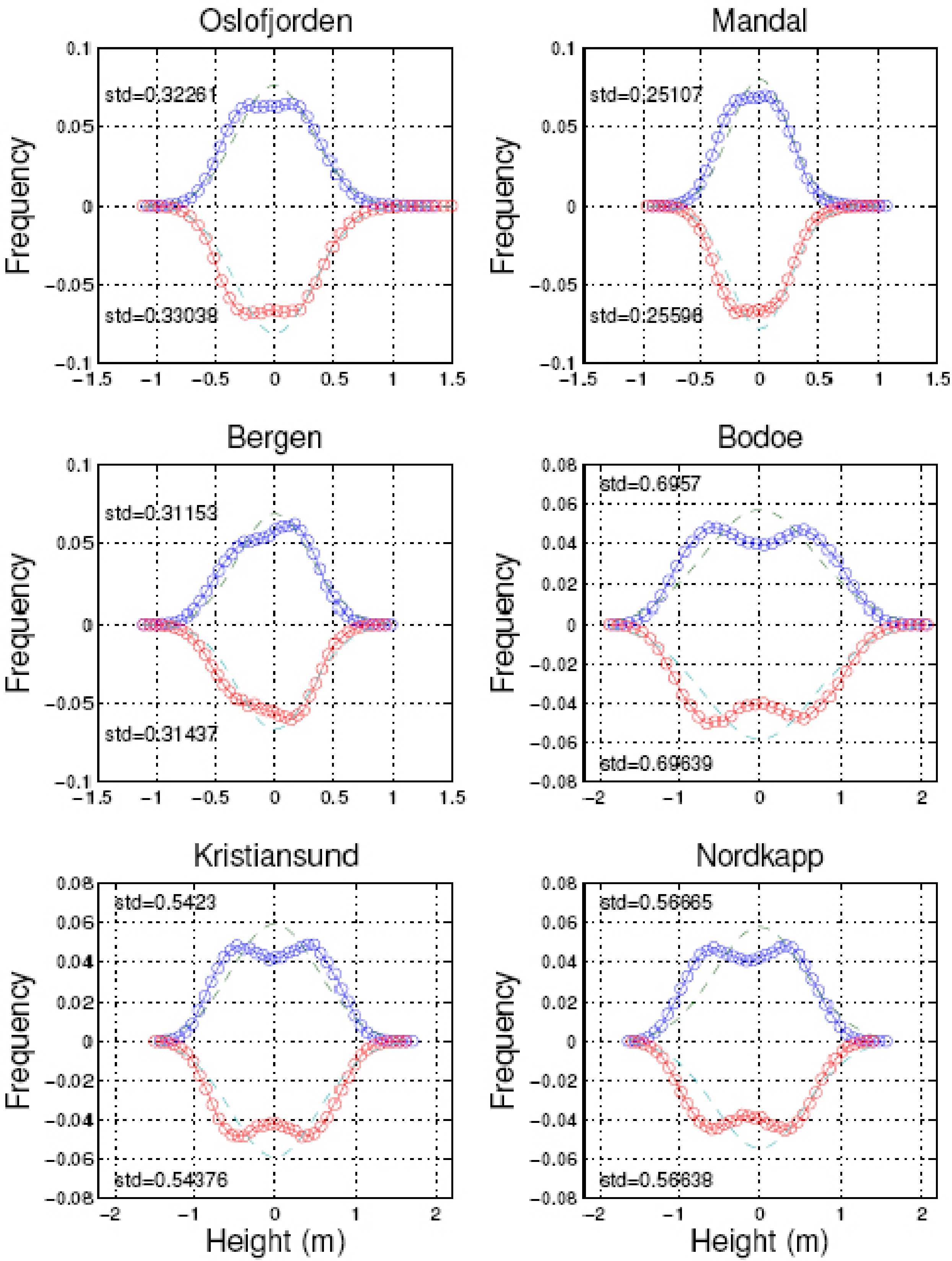


Figure 6.1 *Bi-histograms of SLH at six locations along the Norwegian coast. The lower curves correspond to the period 1980–1999 and the upper curves to the period 2030–2049. The histograms were constructed from hourly height data, from the Regclim MPI-GSDIO simulation. The curves are superimposed on Gaussian curves with the same standard deviations. The probability, from the Kolmogorov-Smirnov statistic, that the future and present histograms are statistically the same is 1000 in all cases.*

Consider the result in the Oslo Fjord. The PDFs in both periods have two maxima and as such deviate from a Gaussian distribution (indicated by the dashed line). This is typical of a tidal record because larger probabilities occur near the maxima and minima (when the change in height is slower). Removing the tidal component yields PDFs with smaller standard deviations which are also more nearly Gaussian.

Comparing the curves, we see the standard deviation is nearly the same in the two periods, albeit slightly less in the later period. Similar, but smaller, decreases are seen at the other sites. Comparing the maximum values, we see that larger values occur in the Oslo fjord during the early period than in the future period. However this is not always the case in the other locations.

The maximum SLH values correspond to extreme events, such as storm surges. As these are of low probability, comparing them in this way is highly uncertain. A better approach is to seek significant changes in the PDFs themselves. To this end, we use the Kolmogorov-Smirnov test (e.g. Press et al., 1992). This allows one to assess the probability that two PDFs are statistically distinguishable (i.e. are drawn from different samples). In all cases, the probability from the K-S statistic was 1000, indicating the PDFs are statistically identical. So despite small differences in extreme values, there is no consistent change between the periods.

We find that the PDFs are indistinguishable at all sites along the coast. In fact the only noticeable systematic difference is a geographic one: the standard deviation is greater in the north, reflecting larger tides there.

The results from the other scenario simulations were the same. We saw no significant difference in the bi-histograms, even over 100 years. So these runs do not support a (detectable) change in sea level height variability due to changes in atmospheric forcing.

In fact the K-S statistic is less sensitive to deviations in the wings of distributions than in the center and so is not an ideal way to assess changes in extrema. An alternative is the Anderson-Darling statistic, which is equally sensitive to deviations across the range of values (e.g. LaCasce, 2005). However the A-D test cannot be used to compare two empirical distributions, as in the present case.

In fact, some differences in extrema were seen by Debernard et al. (2002) and Røed and Debernard (2005), using different statistical techniques. To gauge changes in the extrema, those authors focussed on the SLH values in the 99-percentile range, and studied how that population changed in time. In some of the scenarios they found evidence for significant increases in extrema in localized regions along the west and north coast of Norway. However the changes were not consistent between the climate scenarios (IS92a, A2 or B2), leading the authors to conclude they were more likely a result of undersampled natural variability, and/or related to the choice of global model (MPI v.s. HC).

IPCC (2001a) notes that there was no evidence of a widespread increase in extreme sea level events during the 20th century. However, simulations of the 21st century fields do exhibit increases in extrema. However, these changes vary substantially from region to region, and the result for Norway is uncertain. We thus conclude that there is little significant evidence for an increase in storm surge frequency along the Norwegian coast.

6.3 Mean SLH

Now we consider the likely changes for the mean SLH. For this, we use the IPCC (2001a). The IPCC will release revised projections in early 2007, but this information is still proprietary. We must therefore base our conclusions on the most recent report, as well as on several recent publications.

The last glacial maximum occurred 20,000 years ago. Since then, the sea level has risen over 120 m, following the conversion of the ice sheets into sea water. During the period of most rapid sea level rise, 15,000 to 6,000 years ago, the sea was rising at a rate of 10 mm/year.

Geological records suggest the average rate of rise over the last 6,000 years has been much slower, roughly 5 mm/year, and only about 0.1–0.2 mm/year over the last 3000 years. But tide gauge records during the 20th century suggest a greater rate, from 1.0–2.0 mm/year, during that period. This also represents a higher rate than in the 19th century. The rate over the period 1993–2003 was higher still, around 3 mm/yr.

The current increase in SLH is occurring because of several factors. For one, the heating associated with global warming causes an expansion of sea water. Observational and modelled data suggest that thermal expansion could account for 0.3–0.7 mm/yr of the rise seen during the 20th century. Volumetric increases also occur due to melting glaciers and ice caps, and this account for 0.2–0.4 mm/yr during the 20th century. This melting comes principally from the Greenland and Antarctic ice sheets. SLH is affected in addition by changes in water storage on land (e.g. lakes, river run-off, etc.). However the estimates of these changes over the 20th century are highly uncertain, ranging from –1.1 to 0.4 mm/yr.

Model-based projections of changes from 1990 to 2100 suggest the thermal expansion will be from 0.11 to 0.43 m, corresponding to an average increase comparable to that seen in the 20th century. The model results however suggest this rate will accelerate with time. The change due to melting of glaciers and the Greenland and Antarctic ice sheets ranges from –0.18 m to 0.34 m. The negative value is due largely to projected increases in the Antarctic sheet (see below).

Taking both factors into account, as well as projected changes in the thawing of permafrost and continuing changes from the previous Glacial maximum, the IPCC authors suggest a global-average rise of 0.11 to 0.77 m (Figure 6.2). The large range reflects the large uncertainty in the model results. The models agree better during the first half of the projected 21st century than during the latter half. The projections for 2100 vary by as much as 50 %.

While the models exhibit broad agreement on changes in the global average height, the regional variations in the different model simulations are very large (Figure 6.3). The 100 year projections for the Norwegian Coast range from roughly 0.05 to 0.5 m. The projections are, however, positive in all cases, so one should expect to experience an increase in this region.

The IPCC (2001a) report reflects thinking and modelling prior to 2001. Of course, more results are emerging. Of particular concern is the observed increase in the melt rate of the Greenland and Iceland ice sheets, which could increase the rate of sea level rise to as much as 10 mm/year (Overpeck et al., 2006). In addition, direct satellite measurements of the Antarctic Ice Sheet suggest it is losing mass at 150 +/– 80 km^3 per year since 2002 (Velicogna and Wahr, 2006). This is equivalent to a 0.4 mm/yr rise in the global average SLH, quite different from the IPCC 2001 report which suggested the Antarctic contribution to SLH could be negative. These discrepancies reflect a continuing lack of understanding about the dynamics of the ice shelves and the way these shelves are represented in climate models.

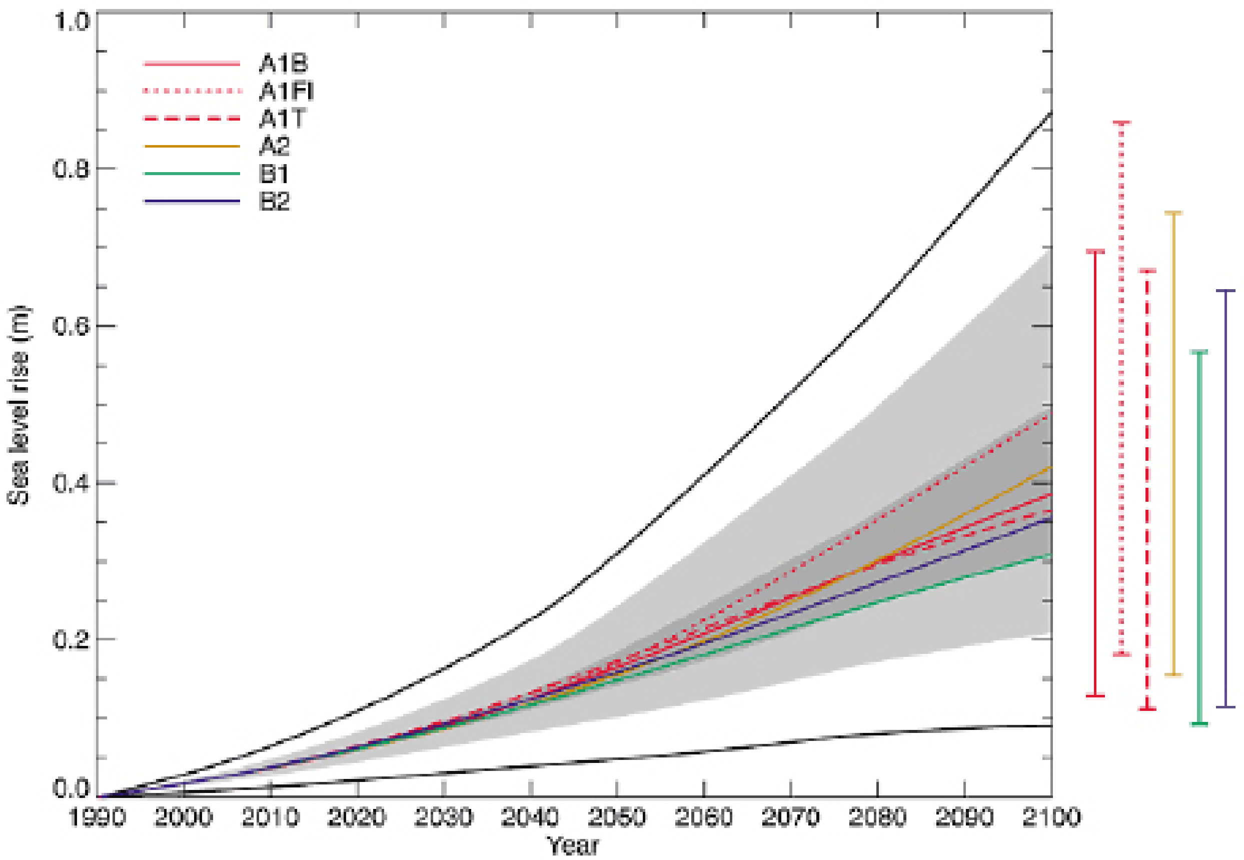


Figure 6.2 *Global average sea level rise 1990 to 2100 for 35 climate scenarios conducted under the IPCC (2001) study. The dark region indicates the range for the average of the simulations, and the light shading the range from all the scenarios. The outer-most lines incorporate uncertainties in land-ice changes, permafrost changes and sediment deposition, but exclude ice-dynamical changes in the West Antarctic ice sheet. (From IPCC, 2001.)*

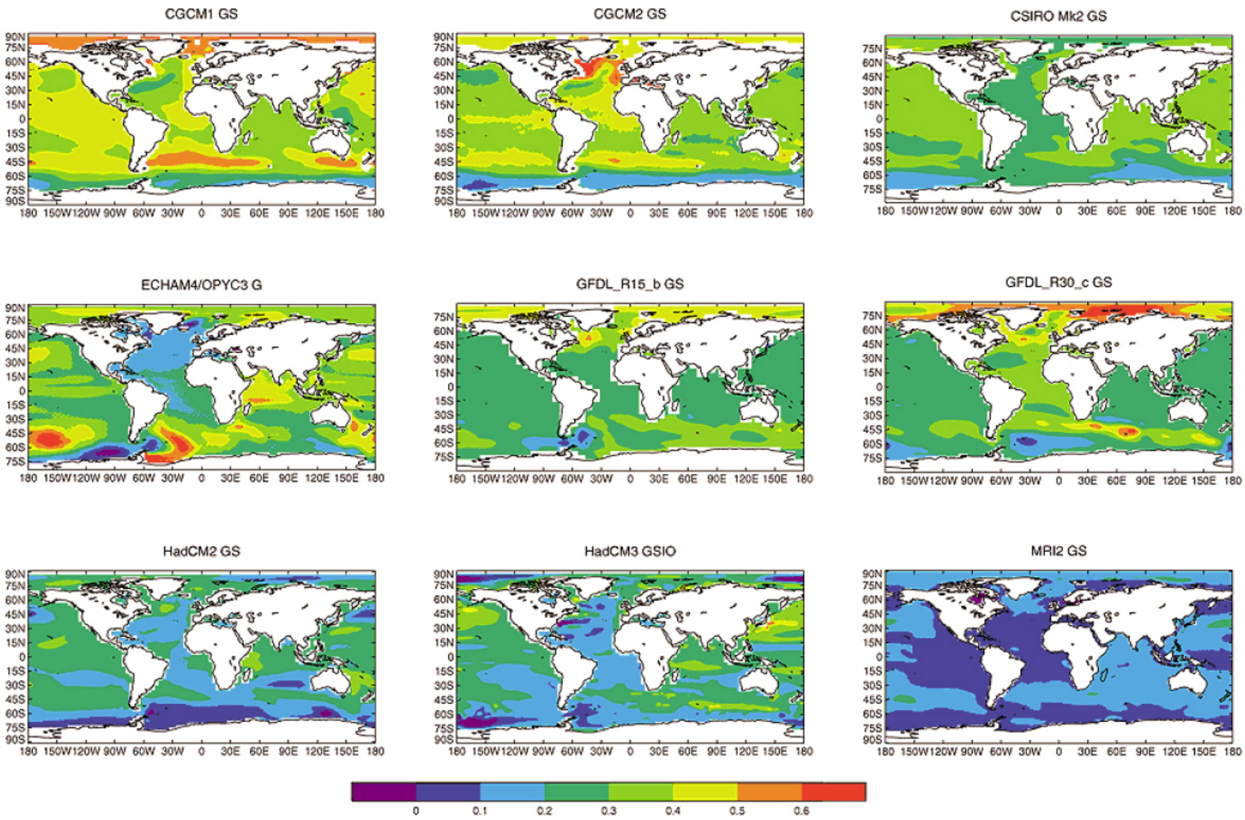


Figure 6.3 *Sea level change in meters over the 21st century resulting from thermal expansion and ocean circulation changes calculated from model experiments following the IS92a climate scenario and including the direct effect of sulphate aerosol. Each field is the difference in sea level change between the last decade of the experiment and the decade 100 years earlier. (From IPCC, 2001.)*

6.4 Continental shift

Due to tectonic motion, the absolute distance from Norway to the center of the earth changes in time and this also impacts the observed sea level along the coast. Estimates of the land uplift for Scandinavia are given in Vestol (2006) and references therein. The estimates have improved in recent years due to precise levelling programs conducted in Denmark, Norway, Sweden and Finland, from 1978 to the present.

The uplift values are derived from tide gauges (corrected for sea level rise) and GPS measurements, in addition to the levelling data. The results suggest a positive shift over most of Scandinavia, with the largest uplift rates, on the order of 8 mm/year, in eastern Sweden. Using Vestol's results, we deduce the following rates for the locations along the coast discussed previously:

Table 6.1 *Continental uplift rates and 50 year uplift at the six locations from Figure 6.1. Estimates derive from the results of Vestol (2006).*

Location	Uplift rate (cm)	50 year uplift (cm)
Oslo	3–5	15–25
Mandal	1	5
Bergen	1	5
Kristiansund	2	10
Bodø	3	15
Nordkapp	2	10

Thus the maximum shift in the Oslo Fjord is comparable to the maximum rise in the mean sea level over the next 50 years from the IPCC report (25 cm). It is less in the other locations, although the uplift will ameliorate the rising sea level there as well. If we take the middle value from the IPCC report of 12.5 cm, we see that there will only be an effective increase in SLH at Mandal and Bergen, and that the sea level will actually fall in Oslo. However, if we accept the more drastic projections which take better account of the melting of the ice sheets, the 50 year sea level rise would be more like 50 cm. Then the continental uplift would be less important, except in the Oslofjord.

6.5 Cumulative effects, extrema

The cumulative effect of the discussed phenomena – short term variability, mean sea level rise and continental uplift – is additive. So the mean sea level rise plus uplift will cause a shift (usually to the right) of the height distributions shown in Figure 6.1. The result is then higher values at the six locations.

Consider as an example the height at Bergen, corrected for mean SLH and uplift. Shown in Figure 6.4 is the cumulative density function (CDF) for the height. The CDF is the integral of the PDF shown in Figure 6.1 and indicates the probability that the height is smaller than the corresponding value on the x-axis; the CDF necessarily asymptotes to 1.0.

The lower curve corresponds to the early period, 1980–1999, while the upper two pertain to the future period, 2030–2049, with two different changes in SLH. The 20 cm value is the largest expected value from the IPCC 2001 report, adjusted down 5 cm for continental uplift. The 45 cm value derives from the Overpeck et al. (2006) prediction of a 50 cm rise, again shifted down 5 cm for the uplift.

For the present period, a height of 50 cm has a value of 0.983, meaning SLH here is greater than 50 cm only 1.7 % of the time. But with the 25 cm shift in SLH, the heights are higher than 50 cm 13.8 % of the time and with a 50 cm shift, the heights are higher roughly 40 % of the time. Alternately, the 99th percentile height in the early period is 0.56 m, while it is 0.75 m and 1.0 m in the two future cases. In addition, the maximum height in the early period is 0.93 m, but increases to 1.18 m and 1.43 m in the late period under the two mean SLH shifts.

In the table below, we list the 99th percentile heights for all six locations from Figure 6.1, using the two mean SLH estimates and correcting for continental uplift. These reflect the extremes in SLH. The largest values are at Bodø, because of the large tides there, whereas the largest differences between the future and present day heights occur at Bergen and Mandal, due to the relatively small uplift values there.

Table 6.2 *99 percentile heights, using the MPI-GSDIO simulations with two estimates of mean SLH rise over 50 years, corrected for the 50 year uplift values in Table 6.1. For Oslo, we use a 20 cm uplift.*

Location	1980/1999	2030/2049 (25 cm)	2030/2049 (50 cm)
	(cm)	(cm)	(cm)
Oslo	69	75	100
Mandal	52	70	95
Bergen	56	75	100
Kristiansund	105	120	145
Bodø	134	144	169
Nordkapp	93	109	134

As is clear here, the most significant factor for future sea level projections and storm surges is the increase in mean SLH. Undoubtedly our forecasts will improve as better projections for mean SLH become available.

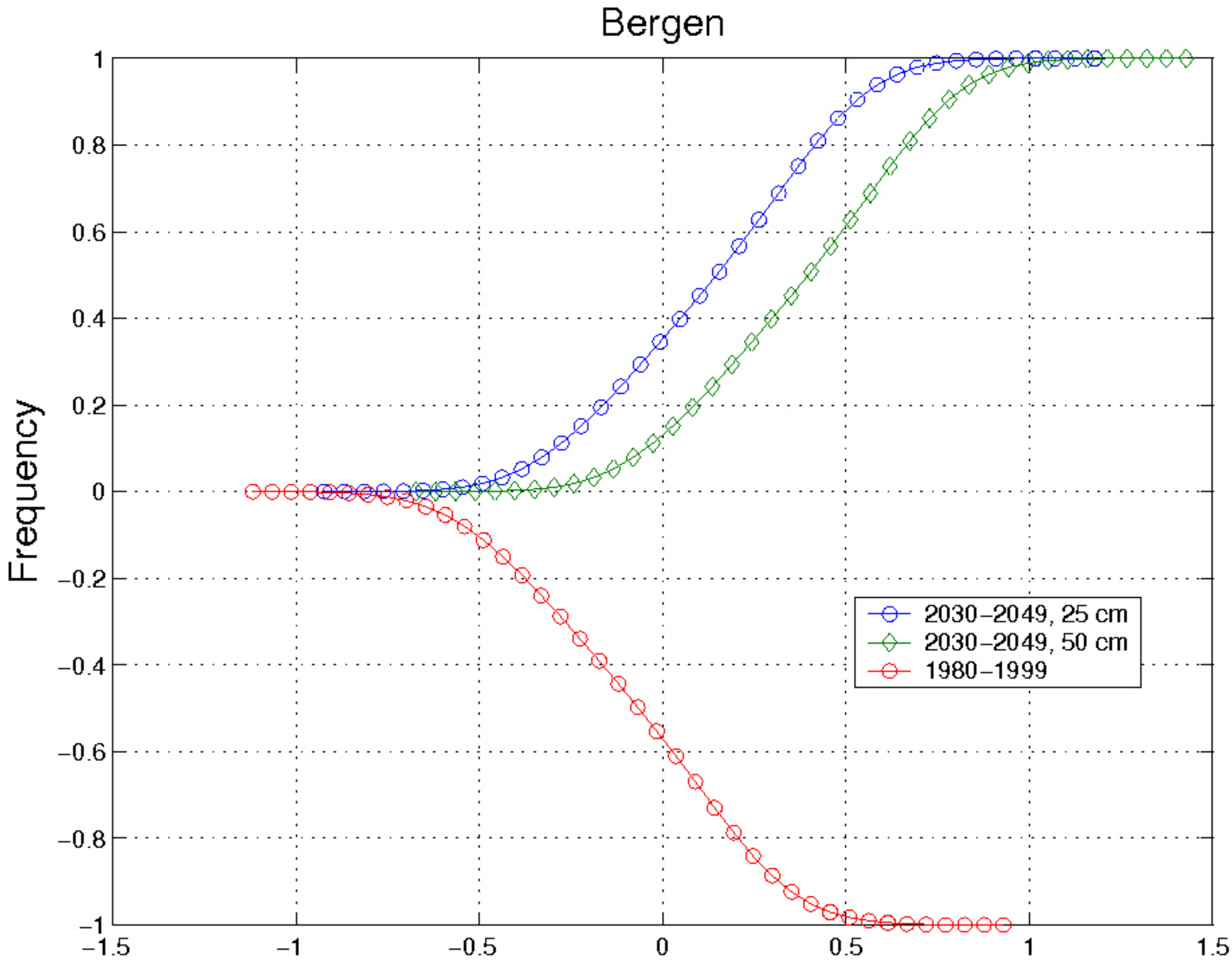


Figure 6.4 *Cumulative density functions for Bergen using the RegClim MPI-GSDIO simulations, with two different shifts in mean SLH in the future period (adjusted for continental uplift). The CDF is the integral of the PDF, shown in Figure 6.1, shifted to account for the mean SLH and the uplift.*

6.6 Conclusions

We have considered possible future changes in sea level height (SLH) along the Norwegian coast, due to short term variability (e.g. storm surges) and due to mean sea level rise. We evaluated changes in the short term variability using climate simulations conducted during the Norwegian RegClim project. These do not exhibit a significant change in the probability distributions of SLH, implying the standard deviations and the frequency of extreme events will not change significantly. Previous analyses suggested an increased frequency of extreme events in certain regions, but these projections were uncertain and varied with the numerical model used. The evidence for more frequent storm surges is therefore weak, in the absence of mean sea level rise.

We evaluated changes in the mean sea level using results published in the IPCC (2001) report. These suggest the sea level height could rise between 0.025 and 0.25 m along the Norwegian coast over the next 50 years. More recent studies, which take into account increased meltwater run-off from the Greenland and Antarctic Ice Shelves, suggest the rise could be twice as large, or up to 0.5 m. The mean rise will be ameliorated by continental uplift in Scandinavia, which will raise the coasts by 5–25 cm. As such, it is conceivable there will be no net change in mean sea level height at some locations along the coast in the next 50 years. But if the mean SLH rise is large as 0.5 m, significant increases in SLH will be evident at all locations.

7 Changes in the frequency of recorded slide events in the decades since 1960

(Kalle Kronholm and Christian Jaedicke, ICG/NGI, Knut Stalsberg and Kari Sletten, NGU)

Key points

- The national slide database comprise a total of ca. 3400 landslides and avalanches, – the oldest dating back to year 900 AD.
- After year 1600 the number of registered slide events per year shows a gentle increase towards a more constant level after 1850.
- The frequency of recorded slides (avalanches, debris slides and rock slides) has increased exponentially in Norway since 1960, but this was found to be due to human factors such as increased use of a database to record observations and an increase in the number of infrastructure units in potential slide terrain.
- Snow avalanches are the slide type causing the highest number of casualities.
- The strongest climate-related signal in the observed changes is that avalanches have moved from primarily dry snow over wet snow to slush flows over the past three decades, indicating more frequent high temperatures and high-intensity rain events when there is snow on the ground.
- Despite this climate-related effect, the most important causes of the observed changes are human and socioeconomic effects.
- To increase the usefulness of a slide database in the future, better coordination between the involved institutions and standardization of the recordings are needed.

7.1 Introduction

Slides are released following a trigger event which may be either external (such as weather events) or internal (such as an earthquake). In Norway slide events are mainly triggered by external events related to weather, for example during periods of high or intense precipitation. Although the earth surface will adjust to local climatic conditions, rapid climate change is likely to affect the frequency of slide events.

The purpose of this chapter is to describe the decadal changes in slide events recorded in Norway, with a special focus on the period since 1960. The analysis covers a) snow avalanches, b) debris slides and c) rock slides. Further, an analysis of the frequency of the sub-types of each hazard type is made. The basis for the analysis is a national slide database.

7.2 Frequencies of slide accidents during the last 100 years

(Knut Stalsberg and Kari Sletten, NGU)

7.2.1 Database on historic slide accidents

«The national slide database» used for these analysis has a total of ca 3400 landslides and avalanches. These events are registered in written sources like newspaper articles, church registers, books of regional history, etc. Only a few registrations in the database are very old (900 AD), but after 1600 the number of registered slide events pr year shows a gentle increase towards a more constant level after 1850 (Figure 7.1).

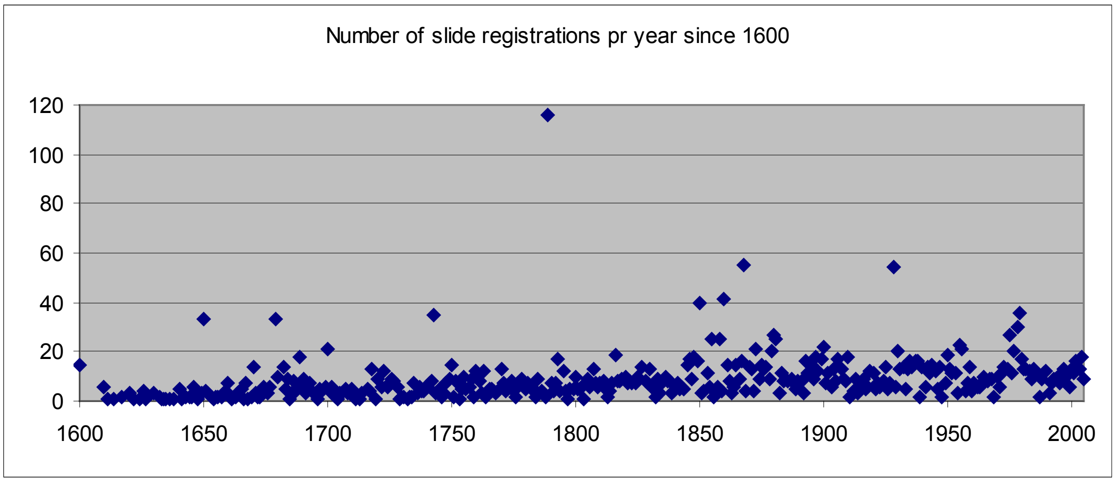


Figure 7.1 Number of slides since 1600, registered in «The national slide database».

Based on the assumption that the geographic structure of Norwegian settlements has been more or less constant since 1905 (Aaheim pers. com.), we have based our analysis on slide accidents from the last 100 years.

Events not causing any damage to people or economic values are only exceptionally described in the database. Nevertheless, we have chosen to work with two selections:

1) All destructive slides (damage to buildings, roads, railroads, livestock, boats, vehicles, farmland, forest or unspecified damage), 1112 slides (Figures 7.2 and 7.3)

2) Slides destructing buildings (casualties in building or damage to building), 413 slides (Figures 7.4 and 7.5)

7.2.2 Slide types

The registration is made from a historical viewpoint and the division in slide types is accordingly simplified. The following slide types are used:

- Rock slides
- Debris flows and debris slides
- Quick clay– and clay slides
- Avalanches
- Rock fall
- Slush flow
- Submarine slides
- Unknown or unspecified slide type

7.2.3 Geographic regions

The slide events are grouped geographically according to the precipitation regions used by RegClim.

7.2.4 Results

Avalanches are the slide type causing the highest number of casualties. The number of casualties pr slide type generally correspond to the number of slide events. The exception from this trend is Western Norway where a high number of victims died in a few large rock slide events.

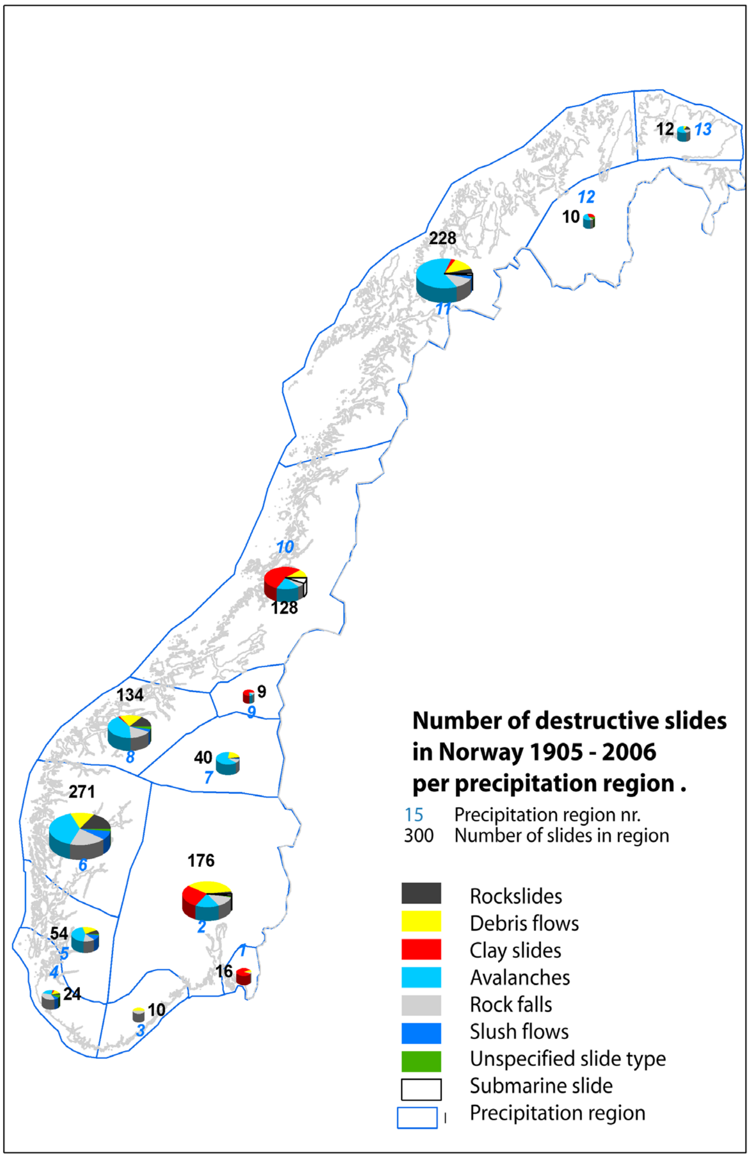


Figure 7.2 Destructive slides in Norway from 1905. See Table 7.1 for details.

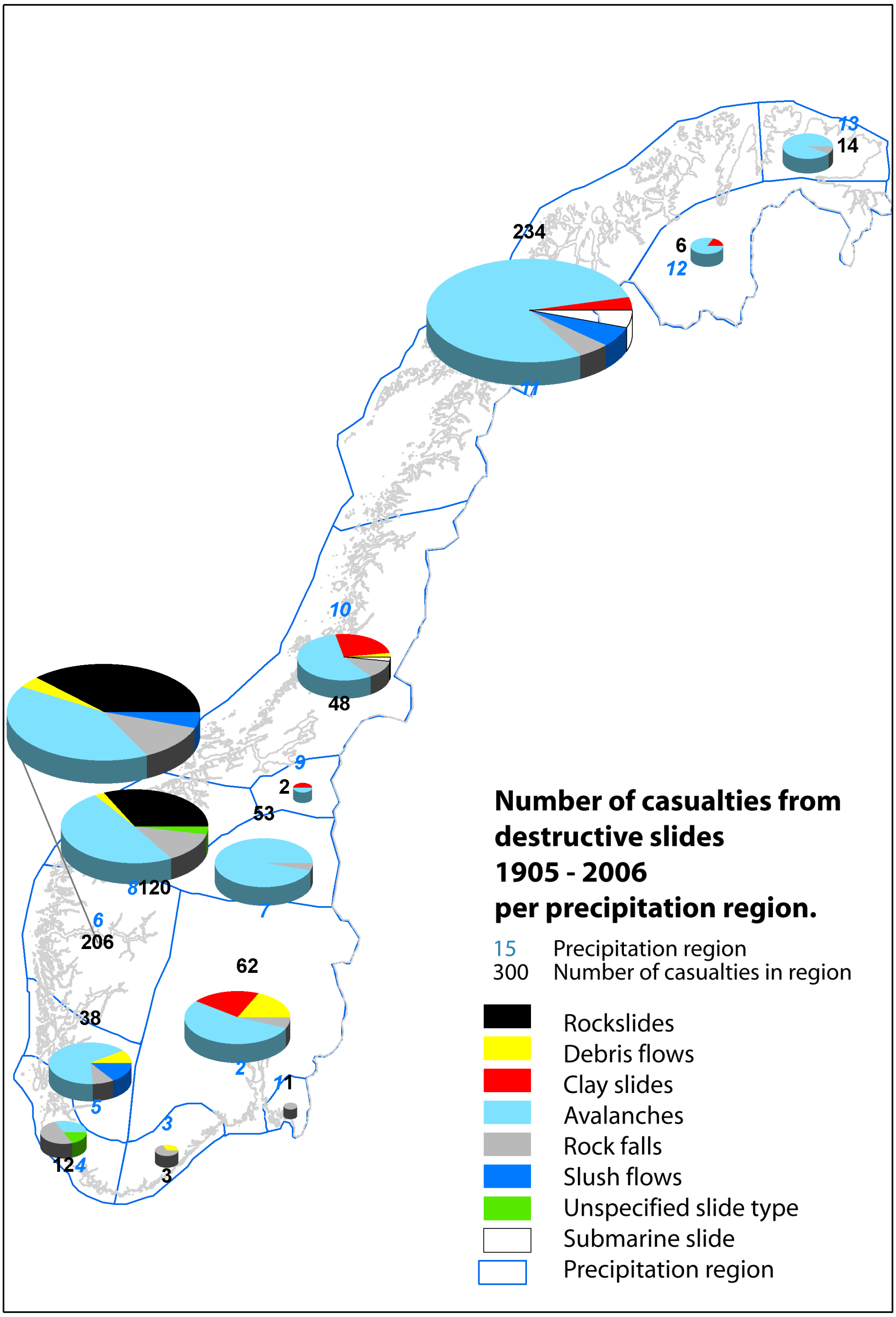


Figure 7.3 Casualties from all destructive slides. See Table 7.1 for details.

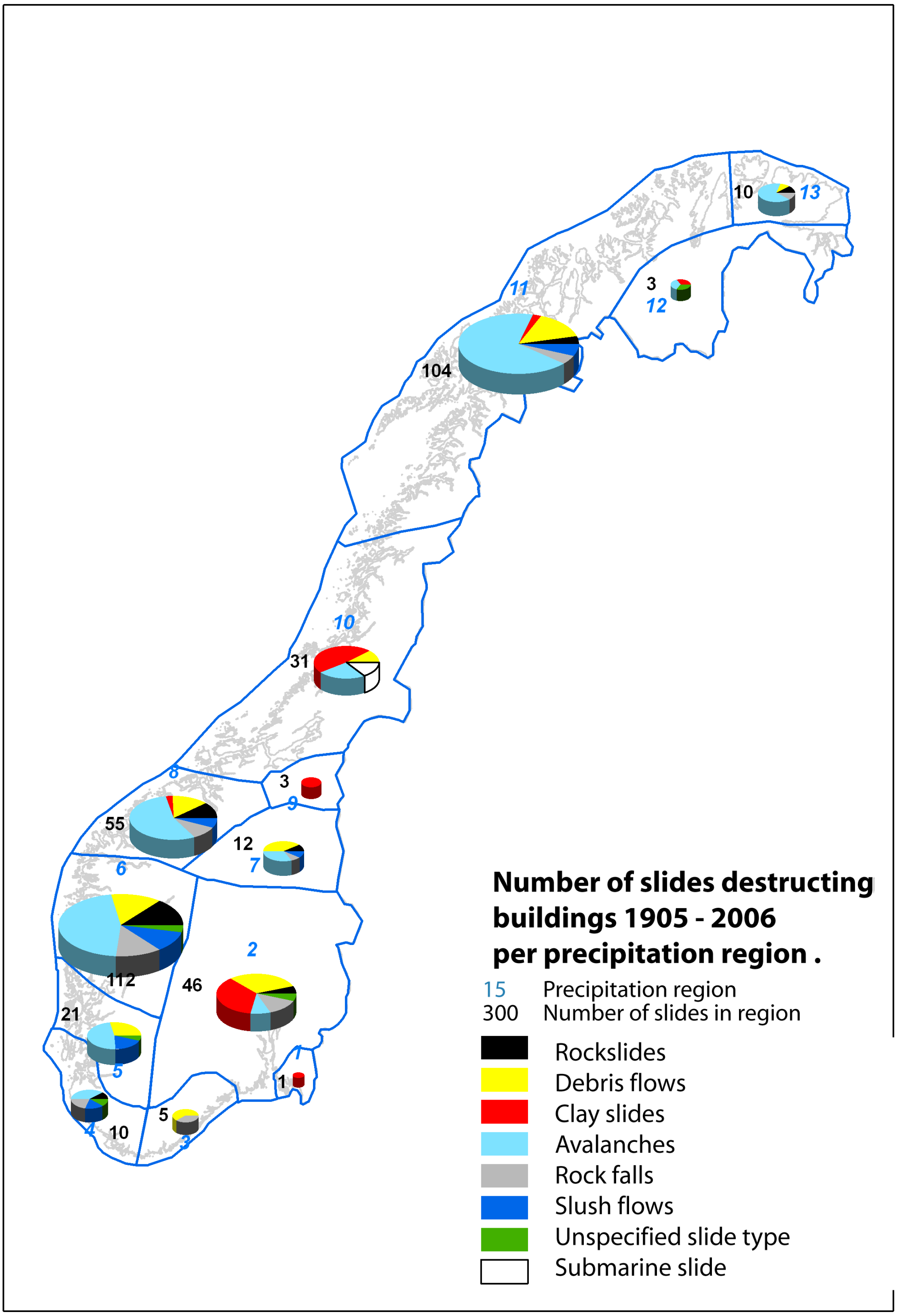


Figure 7.4 *Number of slides destructing buildings. See Table 7.2 for details.*

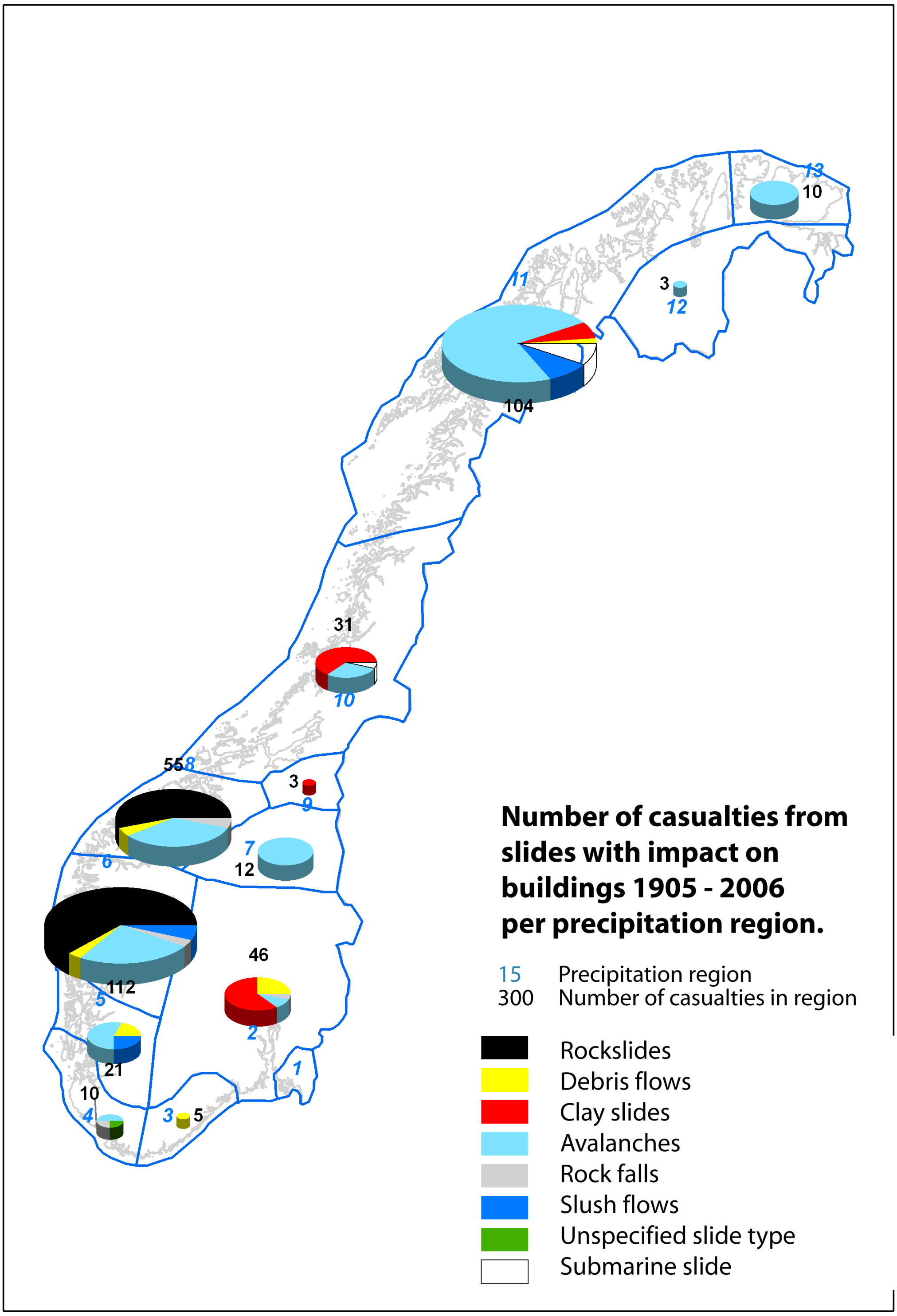


Figure 7.5 *Number of casualties in buildings destroyed by slides. See Table 7.2. for details*

Region	In total		Rock slides		Debris flows		Clay slides		Avalanches		Rock fall		Slush flow		Unspecified		Submarine slides	
	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties
1	16	1			1	0	14	0			1	1						
2	176	62	4	0	69	10	41	16	36	33	21	3			2	0	3	0
3	10	3			5	1					5	2						
4	24	12	1	0	3	0	1	0	6	4	9	6	2	0	2	2		
5	54	38	4	0	12	3			23	26	9	4	5	5	1	0		
6	271	206	40	82	46	7	1	1	97	85	63	23	18	8	5	0	1	0
7	40	53	1	0	8	0			27	51	3	2	1	0				
8	134	120	17	41	30	3	2	0	53	59	24	14	4	0	4	3		
9	9	2					7	1	1	1	1	0						
10	128	48	1	0	13	1	71	13	28	28	7	5					8	1
11	228	234	9	1	29	2	7	7	147	191	26	12	6	12	1	0	3	9
12	10	6					3	1	5	5	1	0			1	0		
13	12	14	2	0	1	0			7	13	2	1						
SUM	1112	799	79	124	217	27	147	39	430	496	172	73	36	25	16	5	15	10

Table 7.1 *All destructive slides in Norway for the last 100 years with the number of casualties. Slide events are grouped according to the precipitation regions used by RegClim.*

Region	In total		Rock slides		Debris flows		Clay slides		Avalanches		Rock falls		Slush flow		Unspecified		Submarine slides	
	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties	slides	casualties
1	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
2	46	24	2	0	16	6	15	15	5	2	6	1	0	0	2	0	0	0
3	5	1	0	0	3	1	0	0	0	0	2	0	0	0	0	0	0	0
4	10	4	1	0	0	0	0	0	4	2	2	1	2	0	1	1	0	0
5	21	16	0	0	6	3	0	0	10	9	0	0	4	4	1	0	0	0
6	112	129	13	78	19	4	0	0	50	38	17	3	10	6	3	0	0	0
7	12	17	1	0	5	0	0	0	4	17	1	0	1	0	0	0	0	0
8	55	74	5	40	9	3	2	0	31	28	5	3	3	0	0	0	0	0
9	3	1	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0
10	31	21	0	0	3	0	15	13	9	7	0	0	0	0	0	0	4	1
11	104	132	3	1	14	2	3	7	73	101	4	0	5	12	1	0	1	9
12	3	1	0	0	0	0	1	0	1	1	0	0	0	0	1	0	0	0
13	10	13	1	0	1	0	0	0	7	13	1	0	0	0	0	0	0	0
SUM	413	433	26	119	76	19	40	36	194	218	38	8	25	22	9	1	5	10

Table 7.2 *All slide events with impact on buildings.*

7.3 Changes in the frequency of recorded slide events in the decades since 1960

(Kalle Kronholm and Christian Jaedicke, ICG/NGI)

7.3.1 Methods

Database

The database used for the analysis contains data from Norwegian Geotechnical Institute (NGI), the Road Authorities (Statens Vegvesen, SV), and Geological Survey of Norway (NGU). NGI started collecting detailed information about avalanches in the beginning of the 1970s and has also collected information about historical slides from the 1960s. However, historical records rarely provide detailed information about the avalanche sub-type. Events recorded by NGI are mainly events that have interfered with infrastructure and people but also events that have not. SV has mainly collected data from 1980. The events recorded by SV have all affected public roads. The data collected by NGU consists of recent data collected by municipalities and counties, and of historical data collected from newspaper articles and historical books. The NGU dataset is described in more detail in the discussion of the regional changes in destructive slides.

Currently the database holds information about more than 20 000 individual slide events. For the present analysis the 17 362 events which have occurred since 1960 were selected. Most events in the database were associated with interference with people, infrastructure or both. In the present analysis all events were considered without any restrictions on type or degree of damage. The analysis spanned the decades from 1960 to present. In the present decade (2000–2009) only a partial dataset was available.

It is important to note the restrictions in the database. A recorded event means that on the recorded time and location there was an event, but this does not hold true the other way around; not all events are recorded in the database. Further, entries in the database were only made if the user found it useful to record the data. The number and quality of entries therefore depends on the individuals who at any given time were in charge of entering data. Spatial and temporal trends could occur because of this.

Slide types

The database was divided into the following slide types: 1) avalanches (implying slides involving snow), 2) debris slides, 3) rock slides, 4) sub-aqueous slides and 5) icefall. This analysis only discusses the changes in types 1, 2 and 3 (Table 7.3). The main slide types were divided into sub-types based on size (rock slides) or the type of parent material (avalanches and debris slides). In the database it was mandatory to enter the main slide type for each event. Recording the sub-type was optional and has therefore only been recorded for a small number of events.

7.3.2 Results and discussion

Slide frequency

The number of recorded slide events has increased exponentially in the decades since 1960 (Figure 7.6). Even with only half of the present decade passed the present decade already has more recorded events than the previous two decades together.

A part of the increase in recorded slide events may be due to an increase in the natural release frequency of slide events. However, it is more likely that any natural changes in release frequency is masked by a combination of the following factors: 1) an increase in the number of infrastructural units in areas where they may be affected by slides, and 2) an increase in the use of computers where the recorded events can easily be transferred over a number of years. It is therefore impossible to say whether the natural release frequency has changed significantly in the decades since 1960.

Slide type

The relative frequency of the investigated slide types is shown in Figure 7.7. The most noticeable changes are 1) a shift from debris slides to avalanches from the first decade (1960–1969) to the second decade (1970–1979), and 2) an increase in the recorded rock slides at the expense of avalanches from 1980–1989 to 1990–1999 and continuing into the 2000–2009 decade.

Again these changes were caused by a combination of natural factors and factors inherent in the database.

However, compared with the change in slide frequency discussed above and shown in Figure 7.6, natural causes appear to have a stronger signal in the relative frequency of slide types. The high relative frequency of snow avalanches in the 1970–1979 and 1980–1989 decades was partly caused by a number of short periods with very high avalanche activity, mainly in 1979 and 1982. During the two last periods 1990–1999 and 2000–2009 the number of such periods has been noticeably smaller. In the beginning of the 1990s the Road Authorities started to report all (large and small) rockfall events which interfered with the roads. This likely caused at least some of the increase in the relative frequency of rock slides in the 1990–1999 and 2000–2009 decades.

Snow avalanches

The frequency of recorded snow avalanches (Figure 7.8) showed a marked increase (leaving out the last decade where the dataset is not complete) but the increase was not as marked as for all slides in the database. As for the slide frequency described and discussed above, the decadal changes in absolute frequency of recorded avalanches was mainly caused by non-natural factors.

The relative frequency of the avalanche sub-types (Figure 7.9) mainly shows that 1) classification of the sub-types starts in the 1970–1979 decade, and 2) recorded avalanches were getting wetter from the 1980–1989 to the 1990–1999 decade and even more so from the 1990–1999 to the present (2000–2009) decade.

The classification of avalanche sub-types in the 1970–1979 decade was coincident with the start of the avalanche group at NGI in 1973. In the 1970–1979 decade most of the recorded avalanche events were recorded by NGI, with a following strong focus on collecting detailed information from each event. In the following decades the number of avalanches reported by SV increased, and the details about each event were not entered.

Looking only at the avalanches with a defined sub-type (Figure 7.10) and for decades with a decent number of observations (after 1970 when sub-types were recorded properly), there was a decrease in the relative frequency of dry snow avalanches from about 2/3 in the 1980–1989 decade to about 1/2 in the 1990–1999 decade. This was followed accordingly with an increase in mainly wet snow avalanches but also slushflows, which are the wettest avalanche phenomenon. In the present decade the relative frequency of slushflows has further increased from the previous decade. This transition to avalanches involving more water may be caused by climatic factors. For dry snow avalanches the main triggering factor is precipitation falling as snow, whereas for wet snow avalanches the main triggering mechanism is warm temperatures. Slushflows are normally released during periods of fast melting of the snow cover (high temperatures) or rain-on-snow events. Yet, because of the low percentage of avalanches with a defined sub-type, the results are to be treated cautiously.

Debris slides

The frequency of debris slides has increased nearly exponentially in the previous five decades (Figure 7.11). The main reason for the increase in absolute frequency is the same as described above: an increase in reporting frequency. An increase in the natural frequency of debris slides is masked by this.

The definition of debris slide sub-types has improved over the five investigated decades (Figure 7.12). This was likely due to more focus and research on the problem.

Looking only at the observations for which a debris slide sub-type is entered (Figure 7.13) it is evident that the relative frequency of quick clay slides and clay slides has decreased while debris flows and debris slides have increased in relative frequency. Debris flows are sediment flows with high water content and debris slides are sediment flows with low water content. Quick clay and clay slides were mainly a problem in 1950s and 1960s because little was known about how they were triggered. After research on the triggering mechanisms for the quick clay and clay slides it was found that these triggers were primarily human, such as excavating and building in critical areas. With this knowledge the number of quick clay and clay slides decreased. The increase in the relative frequency of debris slides and especially debris flows since the 1980–1989 decade is, together with the changes described above, due to an increase in the number of registrations from roads made by SV. Clay and quick clay slides are a smaller problem on roads than debris flows and slides. The observed changes in debris slide sub-type over the past five decades are therefore expected to be mainly due to non-natural effects.

Rock slides

The number of recorded rock slides has increased exponentially in the five analyzed decades (Figure 7.14). As described above this is not likely due to an increase in the natural release frequency but rather due to an increased interest in using a database to record slide events. Especially from the 1980–1989 decade to the 1990–1999 decade there was a large increase in recorded rock slides. This coincides with the time when SV began to record all rock slides that interfered with roads.

In the database the rock slides are divided into events involving small volumes of rock (< 100 m^3) and events involving large volumes of rock (> 10000 m^3). With the increase in recorded number of rock slide events, the relative frequency of events that were reported with a sub-type decreased (Figure 7.15).

If only rock slide events with a defined sub-type are selected for analysis, it appears that smaller rock slides are observed more frequently in the more recent decades. Yet, the low number of observations in each decade makes any observed trends very uncertain.

7.3.3 Summary and conclusions

Over the last five decades there has been an exponential increase in the number of recorded avalanches, debris slides and rock slides. This is primarily due to human and socioeconomic factors. First, an increase in the use of digital databases to report observations has meant an increase in the frequency of reported slides. Second, an increase in the number of infrastructural units which may be affected by slide events has meant that more slide events have interfered with our everyday lives, and thereby has been recorded.

Avalanches (slides involving snow with a varying degree of water saturation) have increased in wetness over the past four decades (since 1970). The reason may be a shift from weather events triggering dry snow avalanches (large events with precipitation as snow) to events triggering wet snow avalanches (high temperatures) and slushflows (high temperatures or rain-on-snow events). From the present analysis the change of avalanche types from dry to wetter sub-types is the only result that is strong enough to make any conclusions on possible changes in triggering events in the decades since 1960.

Debris slides (slides in soil) have also increased in recorded frequency, but this is expected to be due to an increase in the use of recording observed events in a database rather than due to changes in true release frequency. The relative frequency of slides in clay and quick clay has decreased while the relative frequency debris slides and debris flows has increased. This was caused by increased knowledge about the triggering mechanisms for the clay and quick clay slides, whereby they could be largely avoided.

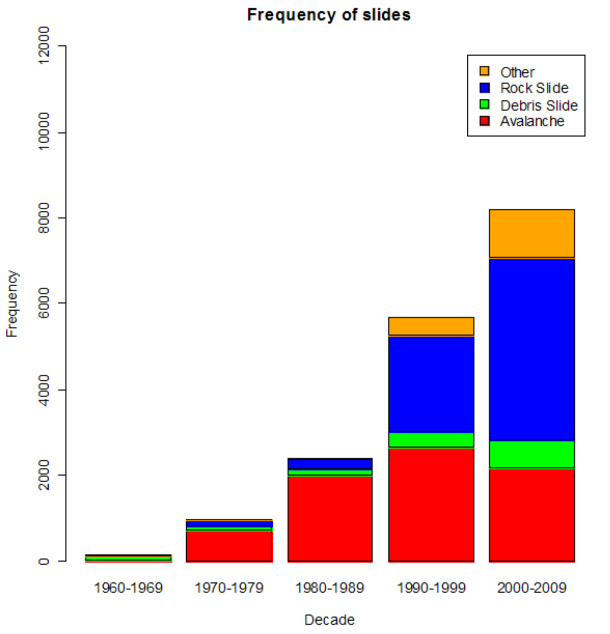
The number of recorded rock slides where the size was recorded was too low to make a detailed analysis of decadal changes in rock slide sizes.

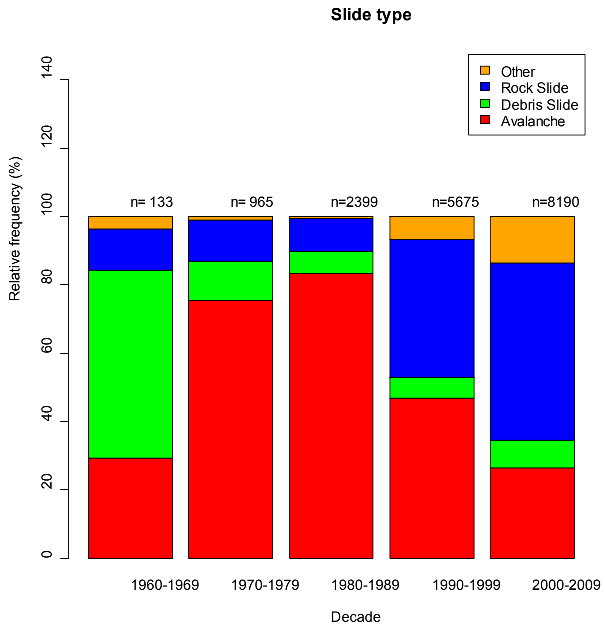
The quality of the database, and especially the expected inherent problems with the increased use of a database to store observations in recent decades, poses strong limitations on the analysis. The observed changes are therefore mainly due to human factors and socioeconomic effects rather than changes in climate and related change in slide release frequency.

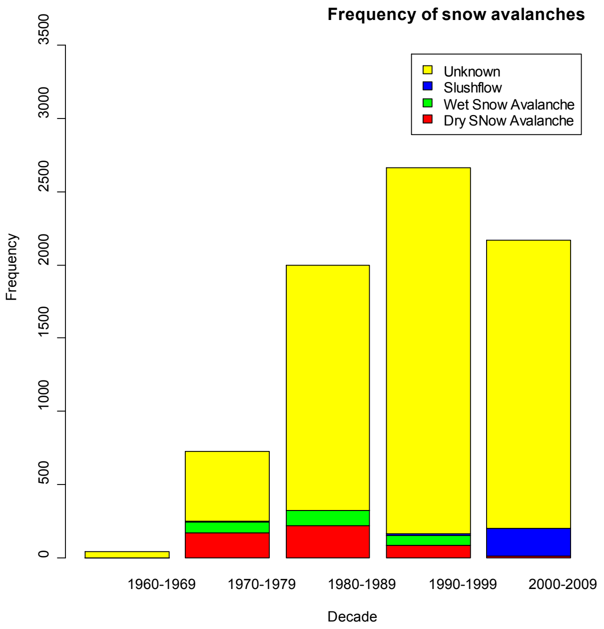
To enable a better analysis of these events in the future, a more homogeneous way of recording slides is needed. This could be achieved by coordinating the recording of slides by the involved authorities and by establishing a national standard for the information recorded for each event.

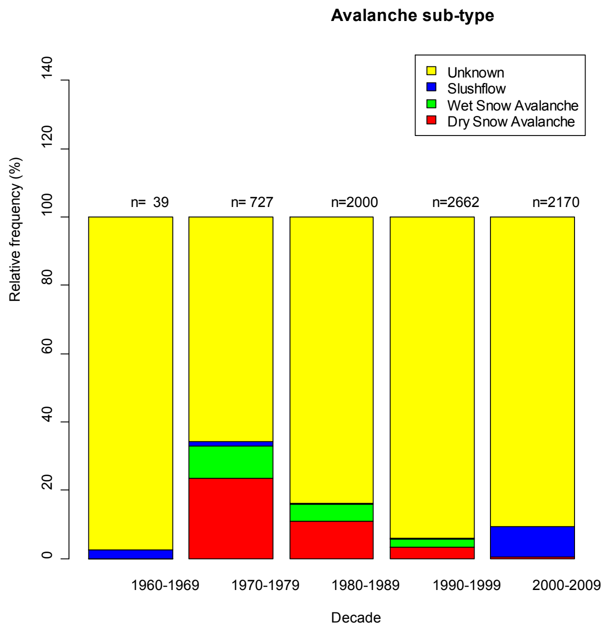
Table 7.3 Definition of the slide types analyzed.

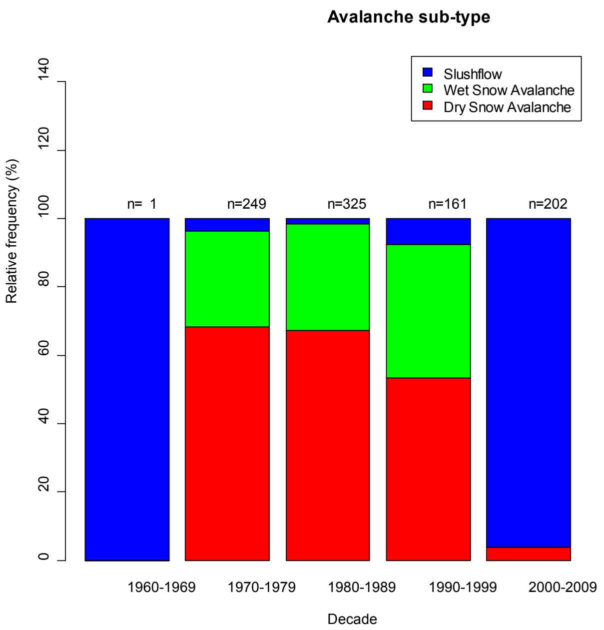
Slide type	Slide sub-type	Description
Avalanche	Dry	Avalanches triggered in dry snow
	Wet	Avalanches triggered in wet snow, possibly with small amounts of free water present
	Slushflow	Flows involving a mix of snow and water
Debris slide	Clay slide	Slides in clayey soils
	Quick clay slide	Slides in quick clay
	Debris slide	Soil slides involving a relatively low amount of water
	Debris flow	Soil slides involving a relatively high amount of water
Rock slide	<100 m^3	Rock slides with small volumes
	≥ 100 m^3 and ≤ 10000 m^3	Rock slides with middle sized volumes
	> 10000 m^3	Rock slides with large volumes











7.6	7.7
7.8	7.9
7.10	

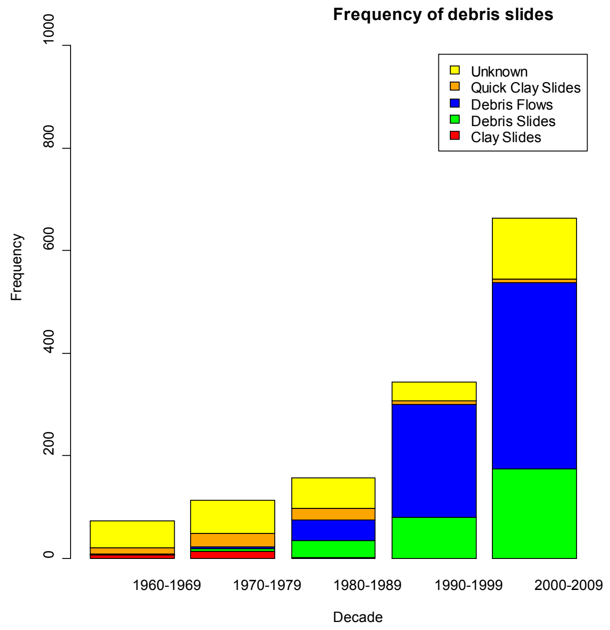
Figure 7.6 *Frequency of recorded slide events subdivided into the different slide types.*

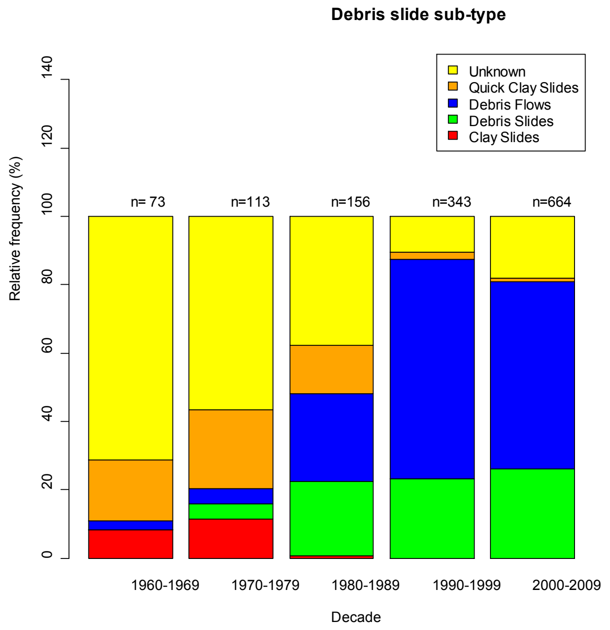
Figure 7.7 *Relative frequency of the investigated slide types.*

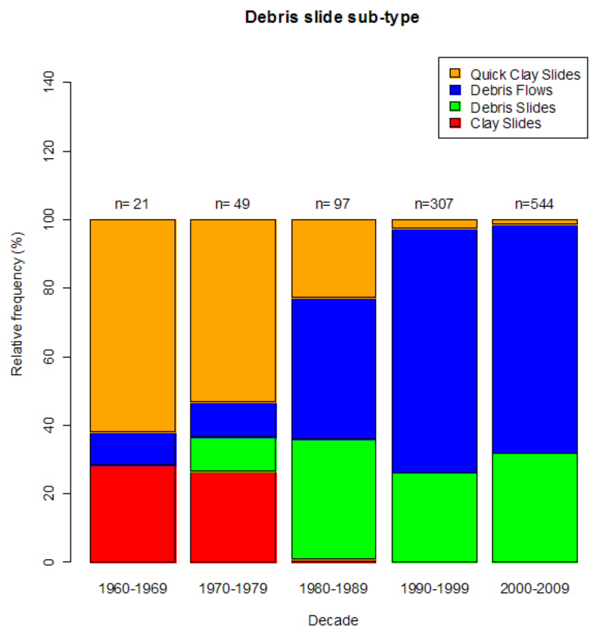
Figure 7.8 *Frequency of avalanches divided into the sub-types.*

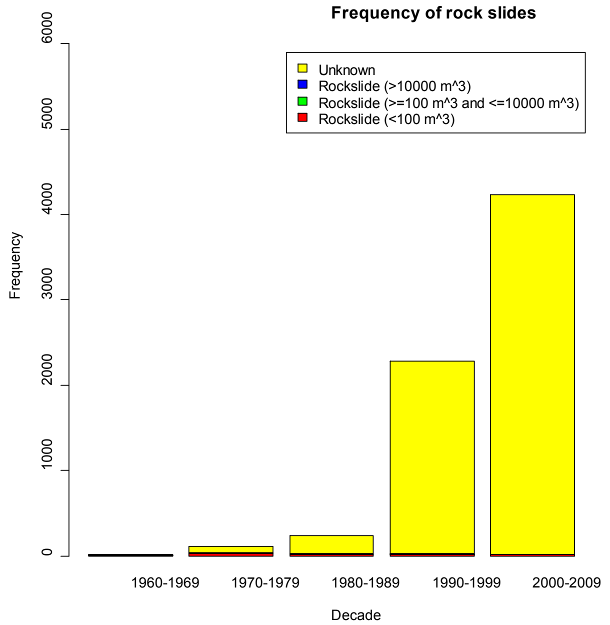
Figure 7.9 *Relative frequency of the avalanche sub-types.*

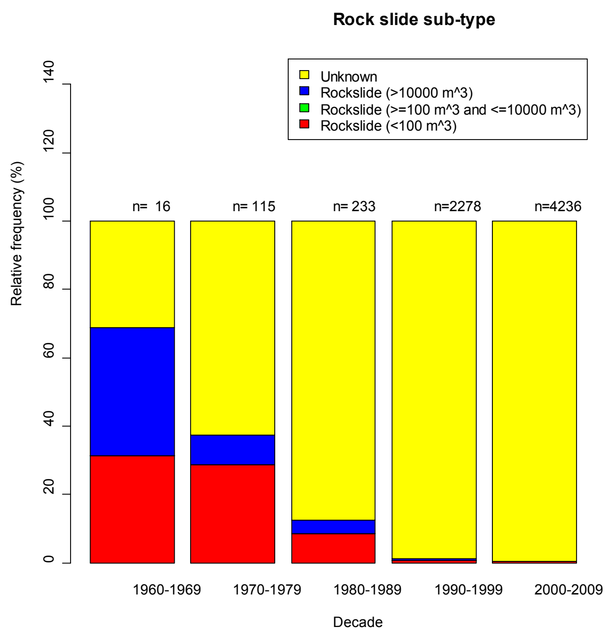
Figure 7.10 *Relative frequency of the avalanche sub-types for those events where sub-type was recorded.*

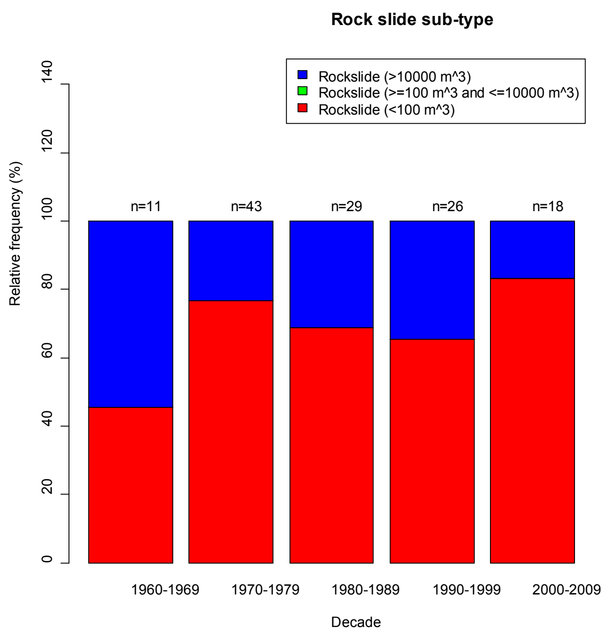

Frequency of debris slides
Unknown
Quick Clay Slides
Debris Flows
Debris Slides
Clay Slides
Frequency
0
200
400
600
800
1000
1960-1969
1970-1979
1980-1989
1990-1999
2000-2009
Decade


Debris slide sub-type
Unknown
Quick Clay Slides
Debris Flows
Debris Slides
Clay Slides
Relative frequency (%)
0
20
40
60
80
100
120
140
n= 73
n=113
n=156
n=343
n=664
1960-1969
1970-1979
1980-1989
1990-1999
2000-2009
Decade


Debris slide sub-type
Quick Clay Slides
Debris Flows
Debris Slides
Clay Slides
Relative frequency (%)
0
20
40
60
80
100
120
140
n= 21
n= 49
n= 97
n=307
n=544
1960-1969
1970-1979
1980-1989
1990-1999
2000-2009
Decade


Frequency of rock slides
Unknown
Rockslide (>10000 m^3)
Rockslide (>=100 m^3 and <=10000 m^3)
Rockslide (<100 m^3)
Frequency
0
1000
2000
3000
4000
5000
6000
1960-1969
1970-1979
1980-1989
1990-1999
2000-2009
Decade


Rock slide sub-type
Unknown
Rockslide (>10000 m^3)
Rockslide (>=100 m^3 and <=10000 m^3)
Rockslide (<100 m^3)
Relative frequency (%)
0
20
40
60
80
100
120
140
n= 16
n= 115
n= 233
n=2278
n=4236
1960-1969
1970-1979
1980-1989
1990-1999
2000-2009
Decade


Rock slide sub-type
Rockslide (>10000 m^3)
Rockslide (>=100 m^3 and <=10000 m^3)
Rockslide (<100 m^3)
Relative frequency (%)
0
20
40
60
80
100
120
140
n=11
n=43
n=29
n=26
n=18
1960-1969
1970-1979
1980-1989
1990-1999
2000-2009
Decade

7.11	**7.12**
7.13	**7.14**
7.15	**7.16**

Figure 7.11 *Frequency of debris slides and the sub types.*

Figure 7.12 *Relative frequency of debris slide sub-types.*

Figure 7.13 *Relative frequency of debris sub-types excluding the observations where no sub-type was entered.*

Figure 7.14 *Frequency of rock slides recorded in the database.*

Figure 7.15 *Relative frequency of the recorded rock slide sub-types.*

Figure 7.16 *Relative frequency of the rock slide events with a sub-type classification.*

8 Changes in damages caused by permafrost

(Ketil Isaksen, met.no)

Key points

- The mountain regions in Norway have an extensive amount of permafrost. In southern Norway the lower boundary of permafrost is about 1450 m a.s.l. in Jotunheimen, 1300 m a.s.l. in Dovrefjell, and 1100 m a.s.l. in Sølen close to Femunden. Preliminary results from Lyngen (Troms) and Romsdalen (Møre and Romsdal) show that the lower limit of mountain permafrost in these areas is lower than earlier estimated, approx. 600–700 m a.s.l. and 1500 m a.s.l., respectively.
- Analyses of permafrost temperature changes in Jotunheimen indicate a ground surface temperature increase of 0.5–1.0 degrees over the last 30–40 years. At present the permafrost is warming considerably. Since 1999 ground temperatures have increased by 0.3 degrees at 15 m depth. Present decadal warming rate at the permafrost table is in the order of 0.04–0.05 °C yr^{-1}.
- The depth of active layer shows significant response to warm summers. The summers of 2002 and 2003 were among the warmest on record (warmest and fourth warmest respectively) in Norway. Active layer depths were 20 % greater in theses summers than previous years.
- In several mountain areas in Norway, ground temperatures are only a few degrees below zero. It is evident that if the observed ground warming proceeds or even accelerates, major changes in mountain permafrost distribution in Norway will be anticipated through the 21st century.
- The geotechnical consequences of permafrost warming in Norway are particularly related to slope stability and the integrity of engineering structures. Permafrost degradation in steep bedrock slopes can lead to increased instability. Studies from the Alps show that a large number of recent rock fall events most likely originated in permafrost areas. Studies of such relationships are in its infancy in Norway.

8.1 Distribution of permafrost in Norway

8.1.1 What is permafrost?

Permafrost is defined as ground remaining frozen for more than one year. If the frost that is formed during the winter does not melt entirely during the summer months, permafrost will form. The upper layer that is thawing during the summer and re-freezes in the winter, the so-called active layer of the permafrost, ranges from 0.5 to 5 meters deep. Today, about one-fourth of the Earth's land surface is covered by permafrost. It is found primarily in polar regions, but also in alpine areas at lower latitudes.

8.1.2 Climate elements determining the distribution of permafrost

Determining the spatial distribution of permafrost and especially its temporal evolution in the context of climate change is still one of the most important objectives in permafrost studies throughout the world. In many inhabited parts of mountain regions the location and extent of permafrost occurrences have to be determined for construction and engineering purposes. The atmospheric climate is the main factor determining the existence of permafrost. However, the spatial distribution, thickness and temperature of permafrost is highly dependent on the temperature at the ground surface. The temperature at the ground surface, although strongly related to climate, is influenced by several other environmental factors such as aspect, snow cover and soil type. Empirically or physically based distribution models (e.g. Etzelmüller et al. 2001, Hoelzle et al., 2005) can be used to delineate the spatial distribution of permafrost over larger areas. But in order to validate the model results and to provide reliable base lines for the model calibration, field measurements for direct or indirect detection of permafrost must be applied. Monitoring of ground- and ground surface temperatures at selected sites are a key variable for determination of permafrost.

8.1.3 Permafrost in Norway

As could be expected, Svalbard is covered almost entirely by permafrost, except for underneath the larger glaciers (Liestøl 1976). It is perhaps less well known that the alpine regions in Norway also have an extensive amount of permafrost. Recent mapping in southern Norway shows that the lower boundary of permafrost, excluding sporadic occurrences and remnants from old (relict) permafrost, is about 1450 meters above sea level (m a.s.l.) in Jotunheimen, 1300 m a.s.l. in Dovrefjell, and 1100 m a.s.l. in Sølen close to Femunden (Ødegård et al. 1996; Etzelmüller et al. 1998; Ødegård et al. 1999; Isaksen et al. 2002; Etzelmüller et al., 2003; Sollid et al., 2003; Hauck et al., 2004; Heggem 2005). Sporadic permafrost is found 300–400 m lower in the terrain, often in palsa bogs (Sollid and Sørbel 1998).

Currently there is little field data on the lower altitudinal limits of mountain permafrost in western- and northern Norway. In 2001 a new permafrost and climate monitoring programme was initiated in the fjord districts of Geiranger and Romsdalen, western Norway, and in Lyngen, northern Norway (Isaksen et al. in prep). In these areas numerous of large rock-slope failures exist and prominent scars are found in the steep rock slopes and well-defined rock-avalanche are deposited in the fjords and valleys (Blikra and Anda, 1997). Preliminary results (Isaksen et al. in prep) show that the lower limit of mountain permafrost in these areas is lower than earlier estimated. Data from Lyngen show that the lower boundary of permafrost is about 600–700 m a.s.l. In some areas in Romsdalen new results suggest that permafrost is widespread at altitudes above 1500 m a.s.l., but the lower permafrost limit is significantly lower in north facing rock walls. In 2002 the programme was extended to also cover Finnmark.

In several mountain areas in Norway, ground temperatures are only a few degrees below zero. Thus, the mountain permafrost is highly sensitive to the projected future climate changes. In response to ongoing and future warming the lower limit of mountain permafrost in Norway will rise in altitude. The geotechnical consequences of permafrost warming are particularly related to slope stability and the integrity of engineering structures. Thus ground temperature monitoring from permafrost boreholes in Norway will provide important thermal data and probable evidence of enhanced thawing of mountain permafrost in the future.

A tentative permafrost map of Norway based on a simple climate-permafrost relationship is shown in Figure 8.1.

In Norway, permafrost studies are performed by several institutes, in co-operation with European research groups, especially from University of Zurich and University of Cardiff. In Norway the University of Oslo has a central role together with the Norwegian Meteorological Institute, the Geological Survey of Norway, the Norwegian Geotechnical Institute, Gjøvik University College, the Norwegian University of Science and Technology and the University Courses on Svalbard.

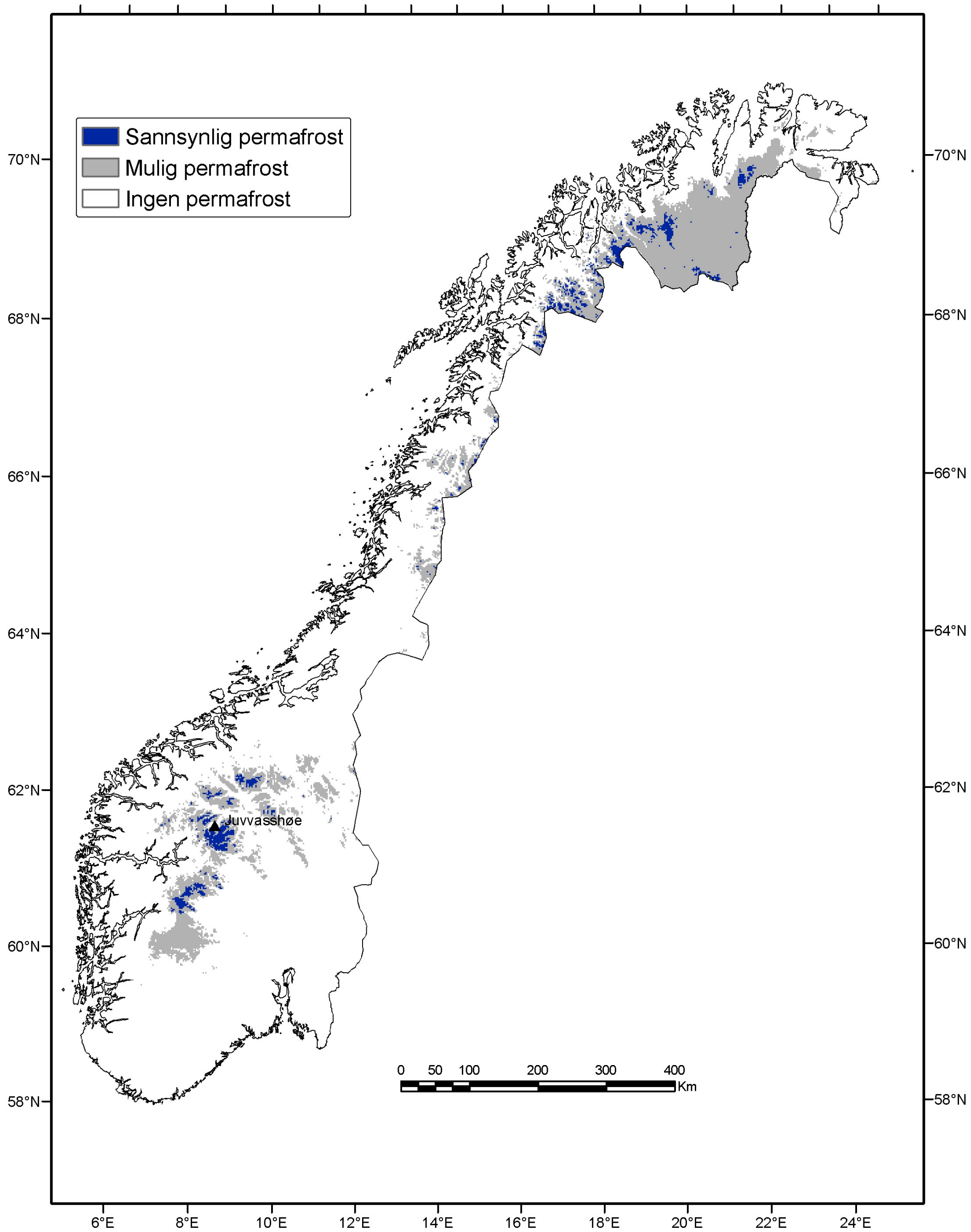


Figure 8.1 *A permafrost map of Norway based on a simple climate-permafrost relationship. The approach using the relation of gridded Mean Annual Air Temperature (MAAT; 1961–90) values to permafrost existence, not considering snow conditions and topographic heterogeneity. Results from studies in southern Norway show that an annual air temperature of –2 to –4°C (grey areas on the map) is a good estimate for the regional limit of the lower mountain permafrost boundary. The blue areas show MAAT lower than –4°C. Here, permafrost is found at most places. The location of a 129 m deep permafrost borehole on Juvvasshøe in Jotunheimen is marked on the map.*

8.2 Current temperature changes in mountain permafrost in Southern Norway

(Ketil Isaksen, met.no)

Monitoring changes in permafrost is in its infancy in Norway and only some few monitoring sites exist. This report presents results from a high-altitude monitoring site in Jotunheimen, southern Norway. Results from more than six years continuous ground temperature monitoring indicate that the permafrost has warmed considerably. The present trend seems to be an accelerated warming during the last few years or decade.

8.2.1 Introduction

Permafrost monitoring provides a valuable supplement to more traditional climate studies, and has been the subject of a three-year EU project called PACE (Permafrost and Climate in Europe), started in December 1997 (Harris et al., 2001). Seven countries participated, including Norway. Seven boreholes more than 100 m deep were drilled in the permafrost in selected alpine areas from Svalbard in the north to Spain in the south. The PACE-borehole network forms a European long-term permafrost monitoring contribution to the worldwide Global Terrestrial Observing System (GTOS), which is under the Global Climate Observing System (GCOS). In Norway, a 129 m deep borehole was drilled in Juvvasshøe (1893 m a.s.l., 61º 40' N, 8º 22' E), southern Norway (for location of borehole, see Figure 8.1). Drilling and instrumentation of the borehole were completed in September 1999. In Norway, the University of Oslo, the Norwegian Meteorological Institute, and the Norwegian Geotechnical Institute and the Gjøvik University College participated in the project.

In permafrost, the geothermal profile is primarily a function of heat conduction. Heat flow from the Earth's interior towards its surface and the heat flux from the energy exchanges at the ground surface determine the near-surface geothermal profile. Temperature perturbations at the surface are propagated downwards and attenuated through time. The annual thermal cycle, with typical amplitude of 20–30 °C at the ground surface generally penetrates to a depth of 15–20 m, but larger perturbations in surface temperature of longer periodicity penetrate much deeper. Thus changes in the subsurface thermal gradient provide a record of recent ground surface temperature history.

Although climate predictions suggest strong warming at high latitudes, the air temperature records in this region show pronounced fluctuations and large inter-annual variability, making identification of longer-term trends more difficult. Recorded ground temperature changes at 40–50 m depth may provide direct evidence of thermal trends at the ground surface during recent decades. Permafrost temperatures represent a systematic running mean that filters the higher frequency signal of the atmosphere and preserves only the low frequency, long-term signals (cf. Lachenbruch and Marshall, 1986). Thus, analyses of permafrost ground temperatures obtained at carefully selected drill sites may constitute a key research tool in climate studies.

8.2.2 Recent temperature changes in permafrost

Permafrost temperature profile in Juvvasshøe show significant near-surface warm-side deviation from linear, with thermal gradient increasing down to 60–70 m depth (Figure 8.2). The deviation is most likely associated with past changes in ground surface temperatures. Analyses indicate a ground surface temperature increase of 0.5 – 1.0 degrees over the last 30–40 years (Isaksen et al., 2001).

Results from more than six years continuous ground temperature monitoring in Juvvasshøe indicate that the permafrost has warmed considerably (Figure 8.2 and 8.3. In Juvvasshøe the annual temperature signal below 15–20 m depth is free of any response to annual or shorter-term temperature variations. At these depths any recorded systematic temperature time variations must correspond to a longer period of several years (e.g., Cermak et al., 2000). Figure 8.3 shows results from the continuous ground temperature monitoring at 15 m depth at Juvvasshøe. Since 1999 ground temperature have increased by 0.3 degrees at

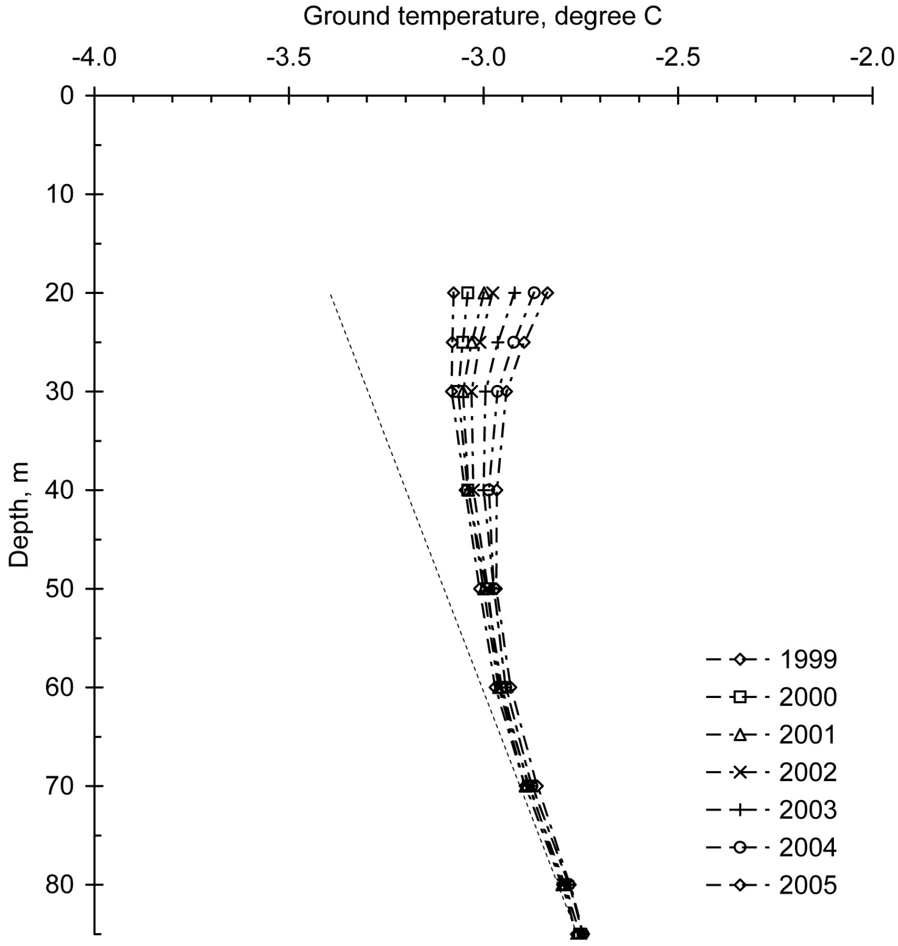
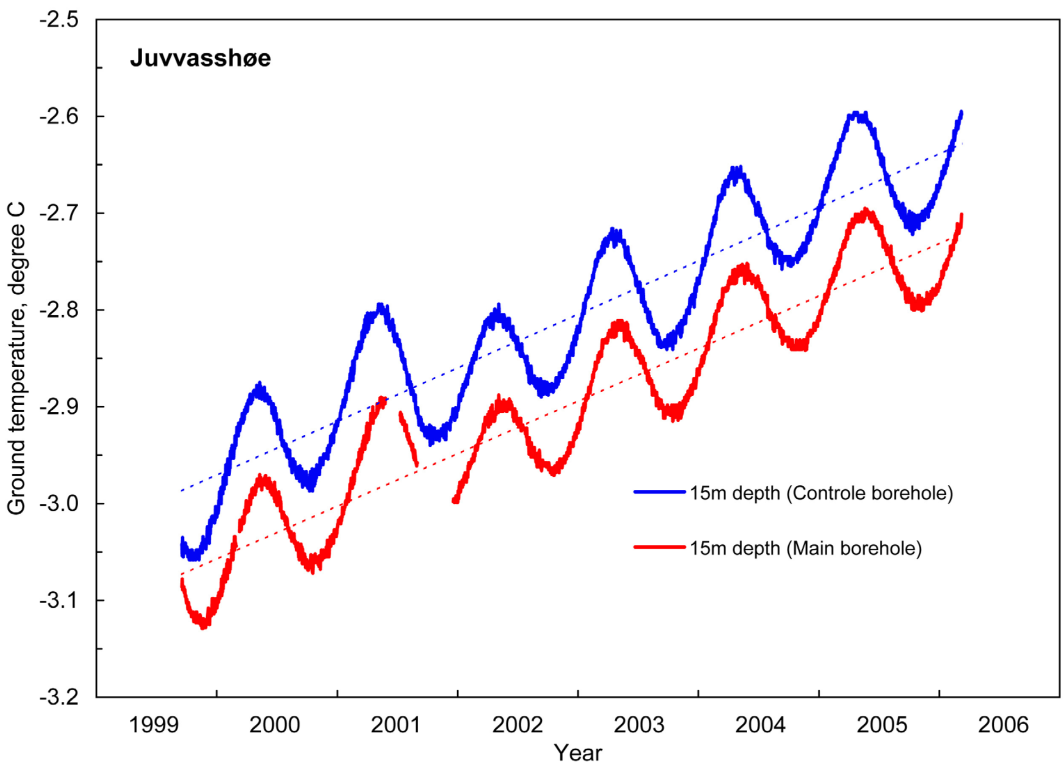


Figure 8.2 (above)
Seven consecutive ground temperature profiles from Juvvasshøe, below zero annual amplitude (ZAA), recorded at 31st December each year (1999–2005). The dotted line is the extrapolated geothermal gradient between 70 and 100 m.

Figure 8.3 (below)
Borehole temperatures in Juvvasshøe between September 1999 and March 2006. The time series are obtained at 15 m depths in the main borehole (red line) and a control borehole (blue line). The 20 m deep control borehole was drilled 13 m away from the main borehole, to detect the thermal influence of the protection structure located at the top of the main borehole. The supplementary shallow hole also provides better resolution of the annual ground thermal variations, and control any possible drift in the thermistors. Time series from both boreholes show a significant on-going ground warming in permafrost in Juvvasshøe. The dotted lines show the linear trends in the series.



15 m depth. The time-series suggest that permafrost is warming at a significant rate. Results show that the ground temperature has increased by 0.2 ºC at 25 m depth and increased by 0.1 ºC at 30 m depth. Observed warming is statistically significant to 60 m depth. This result strongly supports the previous interpretation by Isaksen et al. (2001) that most of the anomalies observed in the temperature depth profiles (cf. Figure 8.2) are associated with surface warming.

Because temperature has been monitored continuously over a period of several years, it is possible to calculate the actual rate of temperature change as a function of depth. Present warming rates at 30 m depth are in the order of 0.025 °C yr^{-1}. Recorded temperature trends at 40–50 m are used to calculate warming rates of the permafrost surface, representative for the last decades. Present decadal warming rate at the permafrost table at Juvvasshøe is in the order of 0.04–0.05 °C yr^{-1} (Isaksen et al., 2007). The present trend is for accelerated warming during the last decade.

In addition depth of active layer shows significant response to warm summers. The summers of 2002 and 2003 were among the warmest on record (warmest and fourth warmest respectively) in Norway. Active layer depths were 20 % greater in theses summers than previous years. It is evident that if the observed ground warming proceeds or even accelerates, major changes in mountain permafrost distribution in Norway will be anticipated through the 21st Century.

8.2.3 Relation to air temperature records

During the instrumental record of air temperature in the 20th Century there have been substantial decadal and multi-decadal temperature variations in the regions of Juvvasshøe. A rather cold period around 1900 was followed by «the early 20th century warming», which culminated in the 1930s. A period of cooling followed, before the recent period of warming, which has dominated most of Scandinavia since the 1960–1970s (Hanssen-Bauer and Førland, 2000). During the period 1965–2004, the trend in annual mean air temperature at Fokstugu, a meteorological station adjacent to the borehole, is positive at the 5% significance level (Mann-Kendall). For the 35 year series, the linear trend is 0.03 °C yr^{-1}. Regression analyses indicate high correlation with the local air temperature observations made at Juvvasshøe. On a monthly basis the coefficient of determination (R2) is 0.97. The somewhat lower decadal trend observed at Fokstugu can be explained by that the pronounced 20th century air temperature fluctuations and large inter-annual variability complicate the analyses of long term trends (e.g., Hanssen-Bauer and Førland, 2000). In one or two years the annual air temperature can differ by more than 3 °C, which is a quite large inter-annual fluctuation. In addition, several studies from other mountain regions around the World (e.g. Seidel and Free, 2003) show that long-term temperature trends at high mountain locations can be significantly different from those at relatively lower elevations. The temperature trends reported on Juvvasshøe will be analysed in more detail in later studies.

Similar observations and even stronger warming are obtained in a borehole in Northern Sweden (Isaksen et al, 2007). Thus permafrost may be warming at a higher rate in Northern Norway, compared to Southern Norway, but more data and analyses are needed to draw more definite conclusions about this.

9 Considerations on changes in frequencies of other natural disasters in Norway, i.e. earth quakes, tsunamis or under-water rock slides

(Kari Sletten (NGU), Knut Stalsberg (NGU), Kalle Kronholm (NGI))

Key points

- Climate change will probably not lead to any changes in the frequencies of earth quakes in Norway.
- A changing climate will probably not cause any increase in the frequency of submarine slides.
- Increased precipitation and thawing of permafrost may cause more frequent rockslides, and thus tsunamis generated by rockslides into fjords or lakes.

Earthquakes and submarine slides

Submarine slides and strong submarine earthquakes may generate tsunamis, but a changing climate will probably not cause any increase in the frequency of earthquakes or submarine slides. Earthquakes and submarine slides are primarily controlled by crust movements, and not by climate.

Rock slides and tsunamis

Rockslides into fjords or lakes may generate tsunamis that may threaten settlements and infrastructure. Water is a critical factor for the stability of failured rock slopes. Increased precipitation may therefore decrease the stability of failured rock slopes, and thereby cause more frequent rockslides. Thawing of permafrost (cf. chapter 8) may also cause more frequent rockslides. Flood waves caused by rock slides may be several tens of metres high and can move over large distances.

10 Changes in vulnerability to natural damage

(Helene Amundsen and Grete K. Hovelsrud, Cicero)

Key points

- Landslides and floods are the most common natural hazards that cause damage in Norway today, and this is expected to be the case over the next 50 years as well.
- Floods are expected to occur at different times of the year compared to the trends that are common at present.
- With respect to landslides, it is uncertain where they will occur in the future, and there is no precise estimate for changes in the frequency of landslides – although an increase in frequency for some regions is expected.
- The climate scenarios provide a clear indication that Norway can expect an increased frequency in all types of weather events that trigger natural hazards. It is however presently not possible to say with certainty where the vulnerability will be greatest, and to which natural hazards.
- It is important to distinguish between increase and change in natural hazards as a result of changing climate conditions. Climate change will lead to changes in seasonal and geographical trends in flooding as well as an increased frequency during the winter season.
- To assess the vulnerability to natural damage, the correlating factors triggering natural hazards as well as a link to locality must be analysed in detail.
- The analyses at the regional level provide indications of expected trends, but we do not have enough detailed information to say with certainty where vulnerability will be the greatest, and to which natural hazards.

The Natural Damage Act covers damage to goods and property that is directly attributable to a natural hazard. The frequency and scale of natural hazards are expected to change as a result of climate change. Natural hazards are related to and can be triggered by weather and climate conditions. When natural hazards cause actual damage, this may have consequences for a society and increase its vulnerability. It is expected that the climate will change beyond the natural fluctuations we have observed until now, and it is important that this be taken into account in the compensation arrangement through the Norwegian National Fund for Natural Damage Assistance. Society can become more exposed and vulnerable to natural damage as a result of climate change. Here, societal vulnerability is seen in connection with the likelihood that Norway, or regions within Norway, will be exposed to an increasing number of natural hazards over the next 50 years. A complete analysis of a society's vulnerability to natural damage cannot be carried out until the areas that are likely to experience natural hazards are seen in the context of their demographic and socioeconomic aspects, as well as their capacity to adapt to the natural damage brought about by climate change.

The first section addresses which types of damage are covered by the Natural Damage Act, and the extent of this damage over the last ten years – in terms of its assessed costs. Data from the Norwegian Agricultural Authority (SLF) from 1996 to 2005 show that, for Norway as a whole, flooding has incurred the greatest damage costs, followed by land- or mudslides and storms/storm surges. Together, these categories constitute over 90 percent of the total assessed damage in the period 1996–2005. The second section draws from the results from chapters 3–8 to analyze the expected change in natural damage throughout the country. Landslides and floods are the most common natural hazards that cause damage in Norway today, and this is expected to be the case over the next 50 years as well. However, floods are expected to occur at different times of the year than has been «normal» up to the present. For example, it is expected that spring flooding will decrease in scale, but that there will be more winter floods. With respect to landslides, it is uncertain where they will occur in the future, and there is no precise estimate for changes in the frequency of landslides – although an increase in frequency for some regions is expected. It is also uncertain how climate change may change the type of slide – such as, increased occurrence of landslides as a result of increased precipitation. More research is needed on which climate elements trigger which types of slide, and how these factors are changing.

The conclusion includes a discussion about the consequences the changing pattern of natural hazards can have for Norway's vulnerability to natural damage. The analyses at the regional level provide indications of expected trends, but we do not have enough detailed information to say with certainty where vulnerability will be the greatest, and to which natural hazards. In addition, this type of analysis should be linked to socio-economic and demographic aspects to obtain a more complete understanding of vulnerability in a society. In general, the climate scenarios provide a clear indication that we can expect an increase in all types of weather that trigger natural hazards. It is therefore important to adapt society so that the scope of the damage is kept to a minimum. Investment in protection, good land-use planning, and good building practices are all important elements to limit damage from natural hazards.

10.1 Survey of damage covered by the Natural Damage Act – scope and distribution

The law that addresses compensation for natural damage is Act no. 7 of 25th March 1994 relating to protection against and compensation for natural damage (the Natural Damage Act). As a supplement, the regulation of assessment of and compensation for natural damage (Regulation of 2nd June 1995, no. 515) is an updated guideline for the assessing natural damage.

This section of the report outlines the types of damage covered by the Natural Damage Act, and provides an overview of the extent and distribution of these types of damage in Norway. In other words, this is an overview of damage that has been registered in the natural damage compensation scheme. We have received statistics from the Norwegian Agricultural Authority (Statens landbruksforvaltning, SLF) that cover the reported cases of natural damage between 1996 and 2005, and these have been used as background for the analysis, along with results from the other partners in the project (met.no, NGI, NGU, and NVE).

10.1.1 Scope of the law

The law stipulates on which grounds compensation will be made for natural damage that is not covered by other insurance arrangements, as well as provides guidelines for promoting and providing funds for protection measures that could limit the scope of natural damage. Natural damage is defined as damage that is directly attributable to a natural disaster, such as a landslide, storm, flood, storm surge, earthquake, or volcanic eruption. When natural damage occurs, the law covers damage to real property that is not covered by other arrangements. The law covers only damage to private property and does not cover damage to property belonging to the state, county, or municipality.

The law does not cover damage caused directly by lightning, frost, or drought, nor is compensation given for damage caused directly by rainfall or ice drift. The same applies to damage attributable to attacks by insects, animals, bacteria, fungi, and so forth. However, full or partial compensation may nevertheless be given for this type of damage when special grounds so indicate (in the data material in our possession, such occurrences are included under «other causes»).

Damage to standing crops, shipping vessels, aircraft, fishing equipment, aerials and signs, equipment for the extraction of crude oil or natural gas, and cash and securities are as a rule not covered by the Natural Damage Act. However, full or partial compensation may be given where special grounds so indicate and where insurance covering such damage is not available through ordinary insurance arrangements.

Damage to forest is not covered by the Natural Damage Act, but compensation is provided in accordance with regulations laid down by the King. Regulations allow for compensation for storm damage to forests when the extent of damage caused by a single event exceeds NOK 200 million. Insurance companies provide coverage up to this amount.

When we evaluate cases of natural damage and societal vulnerability in this report, we are thus referring to damage to real property that falls under the scope of the Natural Damage Act. Thus there is not necessarily any correlation between the magnitude of the natural disaster and the assessed cost of the natural damage. This is discussed in detail below.

10.1.2 Scope and distribution of natural damage (1996–2005)

Data from SLF from 1996 to 2005 shows that for the country as a whole, flooding is the most frequent cause of damage and has the highest assessed damage cost. Flooding is followed by land- and mudslides and storms and storm surges. Together, these categories constitute over 90 percent of the total assessed damage costs in the period 1996–2005. Other causes of damage are ice drift, avalanches, rock slides, and «other causes.»

Looking at the magnitude of natural damage on the basis of assessed damaged costs does not necessarily provide a representative picture of the changes in the frequency or scope of natural hazards. This is because the data does not include the occurrence of natural hazards that do not cause damage covered by the Natural Damage Act, such as avalanches that do not damage real property. Moreover, prevention measures most likely reduce the scale of damage, while construction and new infrastructure can increase the scale of damage from a landslide or flood. High damage cost assessments can be attributed to single events, such as the 1995 flood in eastern Norway called «Vesle Ofsen», which was a major flood in the Glomma region and resulted in high flood-caused damage assessments in 1996 and 1997.

It is difficult to indicate any trend on the basis of the data we possess, which covers the last ten years. In addition, the law has been amended during this period.

Flooding

The counties that have been most at risk for flooding in the period 1996–2005 are Møre og Romsdal, Buskerud, and Hedmark, followed by Oppland and Sør Trøndelag. The «Vesle Ofsen» flood in 1995 resulted in high assessed flood-damage costs 1996–97 in Hedmark and Oppland, and the major flood in Møre og Romsdal in 2004 resulted in high assessed damage costs in this county in 2004 and 2005. The high damage assessments show that flooding has affected areas with private property. It is not necessarily the case that the highest damage assessments mean the greatest risk for natural hazards. It can be the case that one isolated event has caused a great deal of damage, or that an event has occurred in an area with buildings or infrastructure, which can lead to high assessed damage costs.

Slides

There has been an exponential increase in all types of registered slides: landslides, mudslides, rockslides, and avalanches. This is primarily due to the introduction of a digital database, which means that there has been an increase in the reporting of slides. In addition, there has been a strong expansion of infrastructure, also in areas at risk of slides – so that slides have become a part of everyday life for most people and are reported. A final reason for the increase in reported slides is the change in climate. A change in the character of avalanches has been registered: from drier snow to wetter snow as a result of milder weather and increased rainfall.

For slides that occurred in the period 1996–2005, those with highest assessed damage costs were land- and mudslides. During this period, Buskerud was especially affected by land- and mudslides. In 2001, there was a substantial increase in the assessed damage costs compared with 2000, and in the years 2002–2005, the assessed damage costs were considerably higher than in the period 1996–2000. The figures below are based on data from SLF and show the assessed damage costs by county and natural hazard. This presentation does not reflect the legislative changes that took place during this period because these changes are not reflected in the raw data.

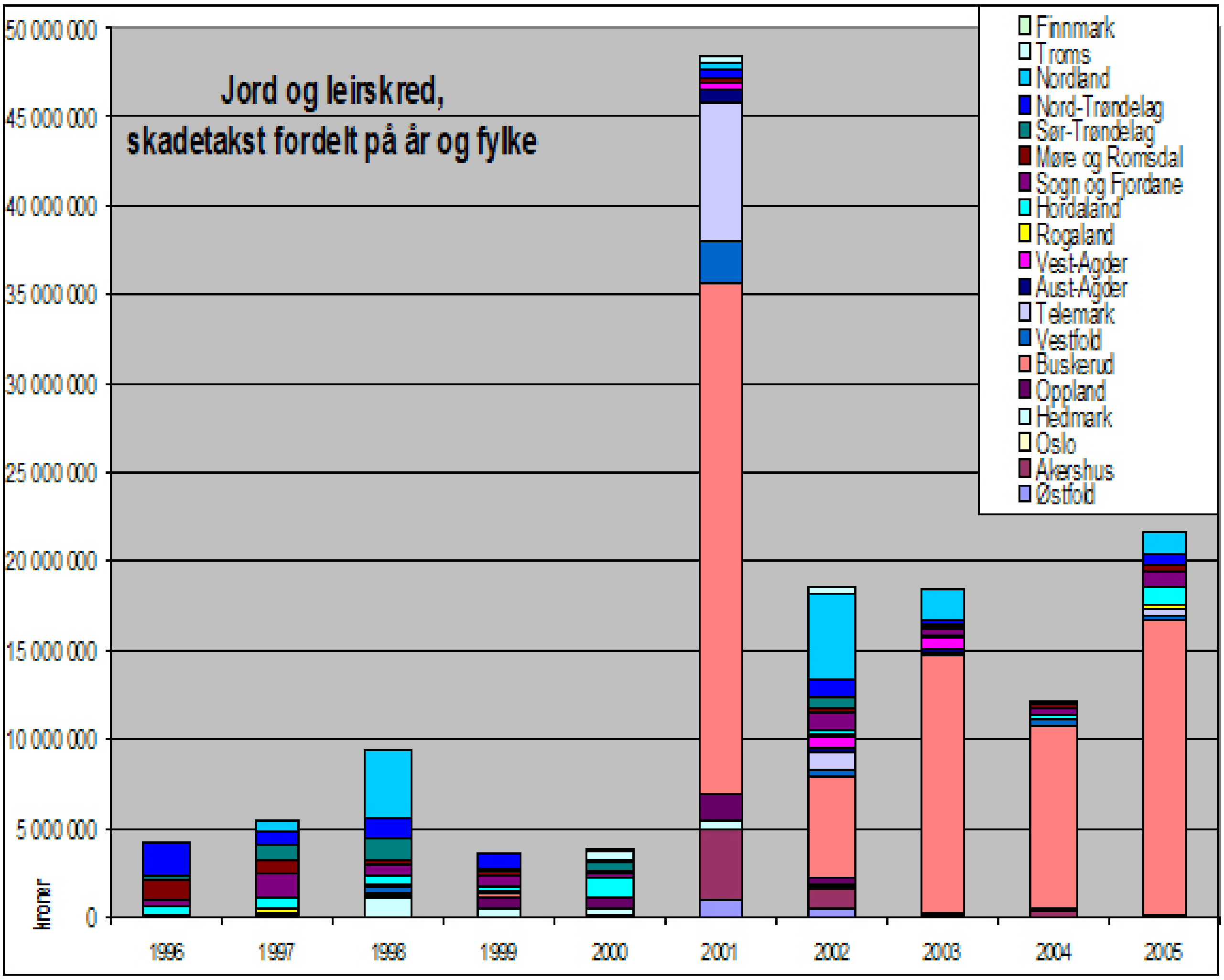


Figure 10.1 Assessed damage costs for land- and mudslides in the period 1996–2005, by county.

When it comes to rockslides, the data from neither SLF nor NGI show a clear trend, apart from indicating that Sogn og Fjordane and Hordaland are at risk for rockslides and have experienced natural damage almost every year during the period in question. It is uncertain whether isolated events or a combination of events form the basis of the assessed damage costs.

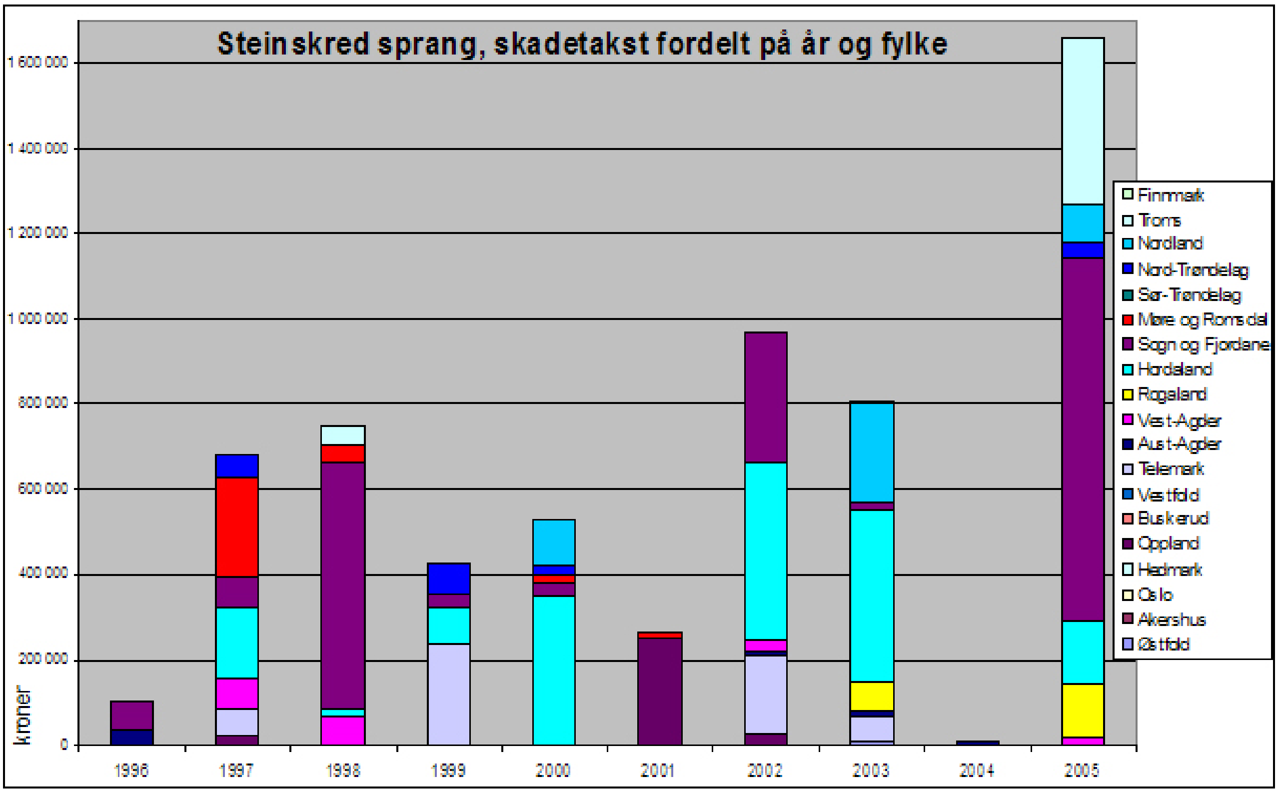


Figure 10.2 Assessed damage costs for rockslides and rockfall, 1996–2005, by county.

Sogn og Fjordane, Møre og Romsdal and Hordaland are at risk for damage from avalanches. The year 2000 in particular resulted in high assessed damage costs from avalanches. More data is required to draw any conclusions about how this might change in the years ahead.

Storms and storm surges

Storms and storm surges have resulted in high assessed damage costs. The counties where the assessed damage costs have been highest during this period are Nordland and Buskerud. In Nordland, Møre og Romsdal, and Sogn og Fjordane, damage costs were assessed for each year in the period 1996–2005. Oslo is the county with the lowest assessed damage costs from storms and storm surges in this period. The figure illustrates how much the assessed damage costs vary for each year. In 1996 and 1999, the assessments were relatively low for storms and storm surges, while in 2001 and 2002 natural damage costs were assessed as being high in all counties except for Oslo, Finnmark (2001) and Aust-Agder (2002).

The total assessed damage costs for the various incidences of natural damage give an indication of which types of natural damage in the period 1996–2005 have led to the highest assessed damage costs. Figure 10.5 shows the total assessed damage cost per year for various causes of damage. It is difficult to infer trends from the data material because the assessed damage costs depend on natural damage from isolated events, and these vary from year to year. The figure illustrates that floods, land- and mudslides, and storms and storm surges have clearly caused the damage with the highest assessed costs. At the same time, it is also clear that there are large variations from year to year, and this means that it is the isolated events that are important. For this reason, it is important to know how the pattern of natural hazards can be expected to change. This next section addresses this by using the information presented in sections 3–8.

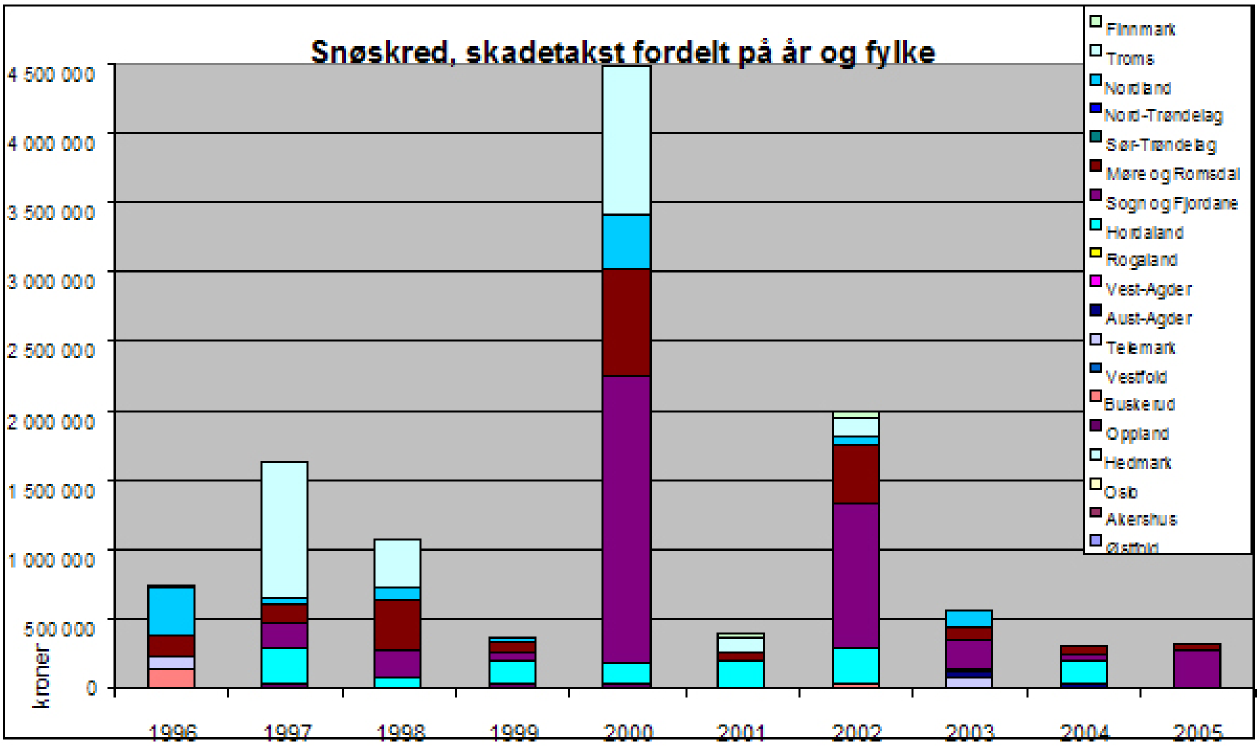


Figure 10.3 *Assessed damage costs from avalanches, 1996–2005, by county.*

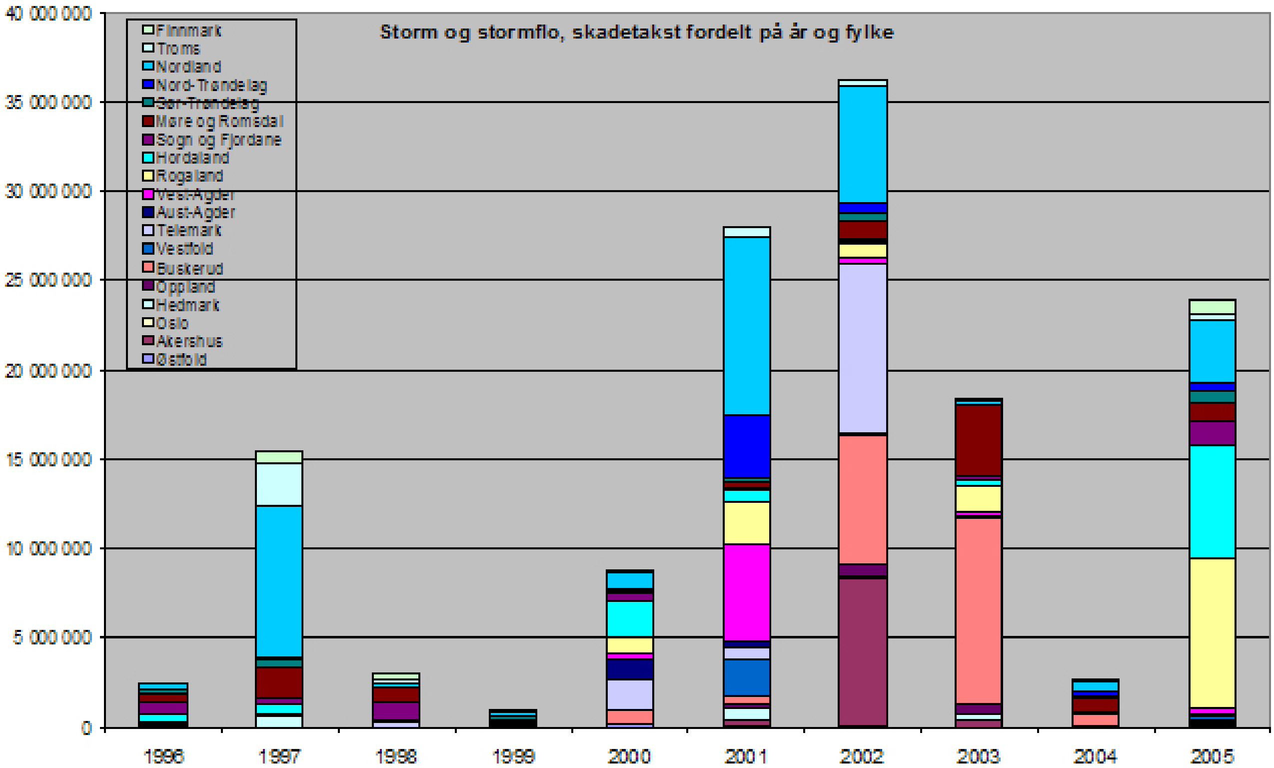


Figure 10.4 *Assessed damage costs from storms and storm surges, 1996–2005, by county.*

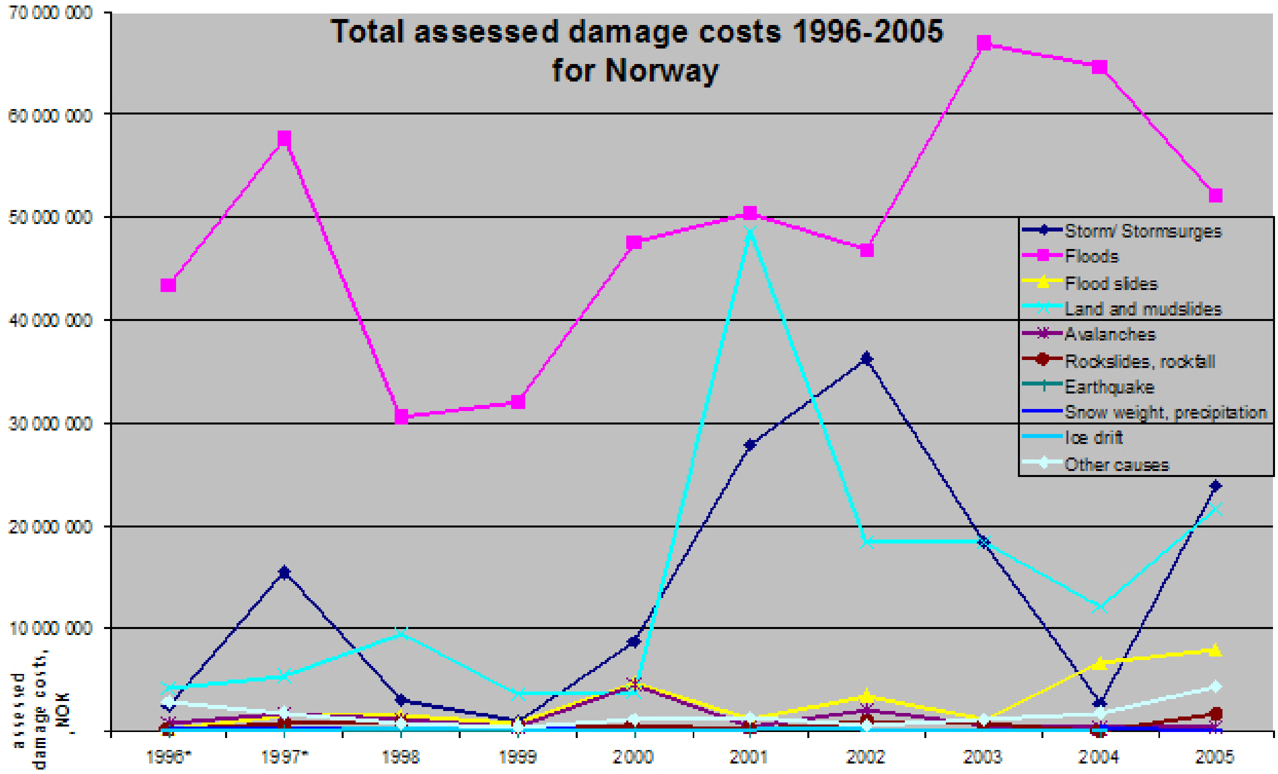


Figure 10.5 *Overview of total assessed damage costs for the various categories of natural hazard, 1996-2005.*
** The «Vesle Ofsen» flood from 1995 is included in the figures for floods in 1996 and 1997.*

10.2 Will society's vulnerability to natural damage change?

On the basis of the results presented in this report, we believe the best approach to analyzing future vulnerability to natural damage is to divide Norway into regions. Although statistics on assessed costs of natural damage are reported at a county level, the county borders do not follow precipitation regions or other major geophysical criteria. For this reason, we have opted to present the results in terms of the 13 precipitation regions identified by met.no (Hanssen-Bauer, 2005) to best harmonize with the other sections of this report. These precipitation regions do not directly correspond with runoff regions, but distinguish relatively well between coastal and inland areas, and between mountainous and lowland areas, which is important in the context of natural hazards.

10.2.1 Natural hazards

Slides and floods are the most common natural hazards that cause damage in Norway, and this can be expected to be the case for the time to come. Over the last ten years, floods have clearly been the cause of the highest assessed damage costs for Norway as a whole. It is expected that floods will occur during different times of the year than what has been «normal» until now. For example, it is expected that spring flooding will be reduced in magnitude, but that there will be more winter floods.

The types of slides that are possible to evaluate in terms of climate change are avalanches, rockslides, landslides, and mudslides. These are triggered by a combination of precipitation, temperature, and wind, depending on factors such as ground conditions, and slope degree. Natural damage that occurs as a result of natural hazards requires that a particular thing is damaged – such as when a slide occurs where infrastructure is built. The challenge here is that it is difficult to provide an indication of exactly where the slides will occur or precise figures for how the frequency of slides may be changed.

This section of the report builds on results from the previous analysis and looks at which climate elements increase the risk of various types of natural hazards, and considers how they correspond with RegClim's scenarios for the next 50 years. This information can then be used to analyze what this will mean overall for the risk of natural damage occurring in various regions, and to analyze whether or in which way society's vulnerability to natural disasters could change.

10.2.2 Conditions that trigger various natural hazards

There are many conditions that enter into the picture when a natural hazard is triggered. Currently, it is not possible to give a clear and exact picture of exactly which conditions play a role since these vary so much from case to case. Nevertheless, it is possible to extrapolate some commonalities. The most important climate elements identified in this report are precipitation, wind, and temperature – in terms of amount, time of year, intensity, and cycle, among other things. Given what we know about which climate elements contribute to triggering the various natural hazards, we can provide an overview of expected natural hazards, and to a certain degree their extent and distribution across the various regions. These results are presented in Table 10.1 and Figure 10.6.

To provide indications about future natural hazards, it is necessary to know what triggers the various types of hazard, as well as look at the regional differences in geography and climate that influence the frequency of the events.

Floods

Intense precipitation need not necessarily lead to flooding. In addition to precipitation, other important factors and their relationship to flooding are as follows:

- Saturated or frozen ground – can cause flooding
- Precipitation that falls as snow – little or no relation to flooding, but depends on temperature conditions
- Increased frequency of multiple intense precipitation events – increases frequency of flooding
- Urban regions – sewer systems can be unsuitable for taking in large amounts of precipitation
- Regulated and unregulated water courses – regulated watercourses can adjust the amount of water
- Cabin developments and their in-roads can be affected by floods – and damage can occur in new areas, and the extent of the damage depends on the size of the built area
- Steep tributaries that converge into large rivers at the bottom of a valley (Østlandet, Sørlandet, Trøndelag), where residential areas are located on the banks of the river – damage potential is particularly high where the annual precipitation is low and the river course is not adapted to high water levels after an intense rainfall. Vestlandet and Nordland are also at risk.

An increase in intense precipitation is expected in the late-summer to early-fall period. As reported in NVE's analysis of 23 catchment areas throughout Norway, seasonal changes in the 50-year floods are expected. On the basis of scenarios that calculate high emissions levels, flooding in the **summer months** is expected to decrease in most areas, except for certain water systems in Trøndelag and Nordland (north of Saltfjellet). **Autumn flooding** is expected to increase in all precipitation regions. **Winter flooding** is expected to increase in all precipitation regions, and the greatest increases are expected in Østlandet, Nord-Vestlandet, and Finnmark. **Spring flooding** shows the greatest variations in the results for changes in the 50-year floods. For high emissions scenarios, there is an expected increase in flooding for all precipitation regions except parts of Sør-Vestlandet. For both scenarios, there is an expected decrease in flooding in the coastal regions of Nord-Vestlandet, in Sørlandet, in Trøndelag, and in Finnmark. In the other precipitation regions, spring flooding is expected to increase. (For a detailed description, see NVE's figures with calculated changes in the 50-year floods, chapter 4.)

Slides

Important factors that can trigger slides include the following:

- Amount of precipitation on the same day as the slide
- Amount of precipitation in the period preceding the slide (3–90 days)
- Average temperature
- Frost cycle
- Number of days with temperatures below freezing
- Rainfall on snow cover
- Wind direction and wind strength

For every type of slide, the values for precipitation lasting more than a day have the greatest effect, but there are variations in the type of slide within and between regions. There is an expected increase in the frequency of slides, particularly in Vestlandet. Because of the uncertainty in the data, it is not possible to quantify expected occurrences of slides.

The most important meteorological parameter with respect to **avalanches** is precipitation and wind strength. For the western coast and the coastline of mid-Norway, day-long precipitation is the most important parameter, while in northern Norway day-long maximum wind strength is the most important. Inland, the 3-day parameter for wind and precipitation is the most important; in inner (southeast) Finnmark, the 3-day maximum wind strength is the most important; for Østlandet the 3-day wind strength is the most important; and in northern Østlandet (north in Hedmark, Oppland, south in Nord-Trøndelag), 3-day precipitation is the most important parameter for the triggering of avalanches (see detailed overview in chapter 6).

And important change that has been observed for avalanches is that they have changed character from dry snow to wet snow, and slush avalanches because of milder weather and increased precipitation in the form of rain. Wet-snow avalanches exert more force than dry-snow avalanches, but do not travel as far. The natural damage from a wet-snow avalanche can thus be greater than the damage caused by a dry-snow avalanche, but it depends on where it occurs. Avalanches are the *most frequent* type of slide, but have so far not led to high assessed damage costs. Climate change can lead to wetter avalanches, and these can cause greater damage if they hit goods and property, because of the force.

For **mudslides and landslides**, the one-day precipitation has the greatest impact along the coast, except for the northern and southern extremes. For southern and southwestern Norway, precipitation events that lasted longer than 3, 10, or 30 days were the most important parameters. In the far north, it was the temperature that mattered the most. Temperature was important for most of the mud- and landslides, and there is a presumed correlation with snowmelt.

Since 1960–1970, there have been fewer registered mudslides. Increased knowledge about how these can be prevented is the explanation for this development. Continued funding for prevention is thus very important to hinder mudslide, also because this type of slide leads to the highest assessed damage costs.

The most important triggering parameter for **rockslides** is, as for mud- and landslides, precipitation along the coast. But the precision of the classification for rockslides is lower than that for avalanches and mud- and landslides. The factors that trigger rockslides vary considerably. A new factor to be taken into account with respect to this type of slide is the thawing of permafrost, which is discussed in chapter 7 (and below).

Storms and storm surges

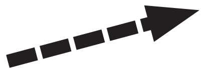
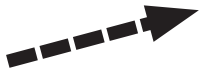
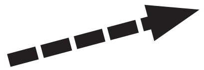
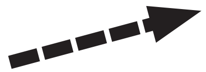
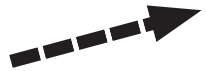
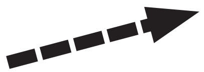
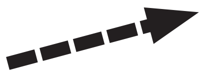
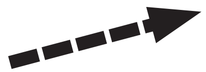
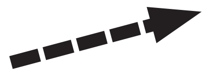
No major changes are expected in storms and storm surges, but this depends on changes in wind, wind strength, and sea-level. No clear trend has been registered with respect to changes in wind conditions. There is uncertainty with respect to sea-level rise. Current projections indicate small changes in the sea level along the Norwegian coast as a result of land rise. But the projections are being modified as new knowledge is accumulated, such as the changes in land ice on Greenland. No significant changes are expected in the variability and frequency of storm surge events up to 2050. The maximum water level with a storm surge depends very much on the sea level, and if global warming leads to a substantial increase in the sea level along the coast, then larger and more frequent storm surge events can be expected.

Permafrost

Change in permafrost depends on temperature, particularly summer temperatures and the length of the summer. It is believed, albeit with relatively high uncertainty, that permafrost continue to warm considerably, and temperature analyses from drill sites in Juvasshøe indicate that the temperature has increased 0.5–1 ^{o}C over the last 30–40 years. The extent of permafrost is not fully documented in Norway, and efforts are being made to develop models that describe the extent of permafrost. If the lower limit for permafrost is raised, then there is a risk of unstable slabs of rock or earth sliding out.

Table 10.1 *Expected natural damage by region.*

This table provides an overview of expected natural damage that has been discussed in this report. This table can be read in conjunction with the map showing expected changes. The map shows changes for smaller regions than those listed here. The table continues on the next page.

	Finnmark	**Nordland** (north of Saltfjellet) **and Troms**	**Trøndelag and Nordland** (south of Saltfjellet)	**Vestlandet**	**Østlandet**
Storm – storm surges It is expected that the most powerful storms will be more frequent, but that these changes will not be significant until after 2050. Flooding in smaller coastal water systems can occur at the same time as storm surges.					
	Uncertain	Uncertain	Uncertain	Uncertain	Uncertain
Floods The projections for flooding apply to changes in the 50-year flood					
	Large increase in winter flooding, decrease in spring and summer flooding, and increase in autumn flooding.	Increase in flooding for all seasons.	Decrease in spring flooding, increase in winter, summer and autumn flooding.	Expected to experience the greatest changes in the most serious floods. Increase in autumn and winter flooding; decrease in spring and summer flooding.	Large increase in winter flooding. Projections show both increase and decrease for spring flooding. Decrease in summer flooding and increase in autumn flooding.
Avalanches Expected increase in avalanches, according to meteorological data. A higher treeline, denser forest, and reduced usage of land for grazing are not taken into account.					
	Stronger wind can lead to a higher frequency of avalanches in this region.	Stronger wind can lead to a higher frequency of avalanches in this region.	No major changes expected.	Increased precipitation is expected to increase the frequency of avalanches.	Stronger wind can lead to a higher frequency of avalanches in some areas.

	Finnmark	**Nordland** (north of Saltfjellet) **and Troms**	**Trøndelag og Nordland** (south of Saltfjellet)	**Vestlandet**	**Østlandet**
Rockslides Expected to increase over the next 100 years, particularly in coastal areas.	Uncertain	Increased frequency of rockslides are expected along the coast.	Uncertain	Increased frequency of rockslides is expected along the coast	Uncertain
Land- and mudslides More frequent slides are expected along the coast, except for the southern regions	Increased frequency of land- mudslides is expected.	Increased frequency of land- and mudslides is expected	Increased frequency of land- and mudslides is expected	Increased frequency of land- and mudslides is expected	Uncertain
Earthquakes No significant changes as a result of climate change	No significant change	No significant change	No significant change	No significant change	No significant change
Ice drift Increase in smaller winter floods can lead to ice drift if the river is frozen. Ice drift can be triggered higher up in the water system than normal and lead to damage to new areas.	Small changes in ice drift	Greater changes in inland areas at higher altitudes.	Uncertain	Uncertain	Uncertain
Permafrost The lower limit for permafrost is raised.	Uncertain	It is possible that the permafrost will thaw in Lyngen	Uncertain	It is possible that the permafrost will thaw in Romsdalen	In Jotunheimen the ground temperature has increased significantly the last 30-40 years. Higher summer temperatures will continue this trend.

Table 10.1 *Continued from previous page*

10.2.3 Vulnerability to natural damage

What is meant by vulnerability: Vulnerability is a concept that describes how exposed a society is to various pressures and which adaptation and coping possibilities are available. In this study, the issue in question is *what are the changes in Norway's vulnerability to natural damage given expected changes in the climate.* Vulnerability to climate change says something about to what degree a system is receptive to or unable to handle the negative impacts of climate change, as well as climate variation and extreme events (IPCC, 2001b). Vulnerability is a function of the character, scope, and degree of climate change and variation in how a system is exposed to climatic hazards, its sensitivity, and its adaptive capacity. Adaptive capacity is defined in the IPCC's Third Assessment Report as 'the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, and to cope with the consequences' (IPCC 2001b, p. 6). Vulnerability to the impacts of climate change can only be evaluated by looking at all factors that affect vulnerability.

Society is vulnerable to natural damage to the degree that natural hazards lead to the suffering of individuals or local communities. Vulnerability is a combination of many factors – that is, it is more than the magnitude of a natural hazard that determines whether a society is vulnerable. Geography, preparedness, the economy, and adaptive strategies are some possible factors that help influence a society's vulnerability.

How vulnerability is analyzed: Analyses of vulnerability look at small, local communities, because it is at the lowest level that it is possible to analyze and consider all the factors that are relevant with respect to the vulnerability of that particular area. Thus without also taking into account the socio-economic aspect, what we can say about natural damage is limited.

For natural damage to be ascertained by law, it must cause damage to real property. The challenge in analyzing the possible impacts of climate change on natural damage lie in the uncertainty of the climate scenarios as well as the complexity of the climate system and other conditions that can help trigger natural hazards. In addition to this, knowledge is needed about how society will develop. Vulnerability to natural damage increases with population density and infrastructure development, and socio-economic and demographic factors lie outside the mandate of this report.

The descriptions in this report of expected increased frequency of natural hazards do not necessarily mean increased natural damage. For example, increased flooding in mountainous regions as a result of earlier snowmelt in the spring will only have an impact on societal vulnerability if the floods occur at the same time that rivers are frozen, triggering ice drift.

To the extent that we can say something about society's vulnerability solely on the basis of information about changes in natural hazards, it must be that new areas will be exposed to flooding. The location of housing communities in relation to where winter flooding is expected to occur must be documented. The local communities located in areas where winter flooding occurs can be expected to be vulnerable. If communities located in flood-exposed areas are not prepared for possible changes in flood patterns as a result of climate change, their vulnerability will increase.

In the material presented above, there is a lot of information that can be used in an assessment of changed vulnerability. But it must be specified that natural hazards must be connected to socio-economic and demographic conditions. Below follows a list of natural hazards that can be worth studying in more detail:

– Populated riverbanks will be more exposed to flooding and higher water levels, and thus these areas can be assumed to be more vulnerable. Many densely populated areas are located on the river banks, and concurrent factors such as greater discharge to the river in the winter and more frequent flooding can cause greater damage in these areas. These areas are potential examples of new vulnerable areas that have not previously been particularly exposed to this type of damage.
– Winter flooding may increase, and one consequence of this can be ice drift when rivers are frozen, or that ice drift occurs farther inland than previously, such that damage can occur in different locations.
– Small tributaries that until now have not had large flows of water will, because of seasonal changes and increased precipitation, be exposed to larger discharges. This will affect the societies in these areas.
– Clear trends for changes in flood patterns: This will result in smaller floods and flood events with ensuing natural damage in some areas, and larger and more comprehensive natural damage in other areas – and the variation in the flood pattern between seasons will be changed. Floods can thus lead to other types of damage than the society has adapted to and damage can be greater as a result. It is not expected that flood damage will be dramatic

in areas that are already adapted to large amounts of precipitation – such as in western Norway – but there can be problems with large amounts of precipitation in eastern Norway in areas that are not adapted to large amounts of precipitation.

– Slides: The frequency of slides is expected to increase – the question is where. Landslides are correlated with precipitation: increased precipitation leads to increased landslides. Given that precipitation is expected to increase throughout Norway, and that at times the precipitation will be intense, the risk of landslide is expected to increase. To what extent a society is vulnerable depends on its location and protection. But it is expected that areas that seldom or never experienced landslides will now be exposed. Thus it must be documented in more detail, at a more local level, whether existing conditions suggest a likelihood of landslides. This type of natural hazard is local in nature. The available data does not provide this type of information, but analyses are currently under development (see *www.geoextreme.no*).

With some certainty we can say that there will be an increase in natural hazards such as floods, avalanches, rockslides, and land- and mudslides (see figure 10.6 below). But at the same time, the frequency, magnitude and scope of these natural hazards vary by region and season. It is also important to understand that there is considerable uncertainty with respect to these results. When it comes to storms, the results today show no clear trend.

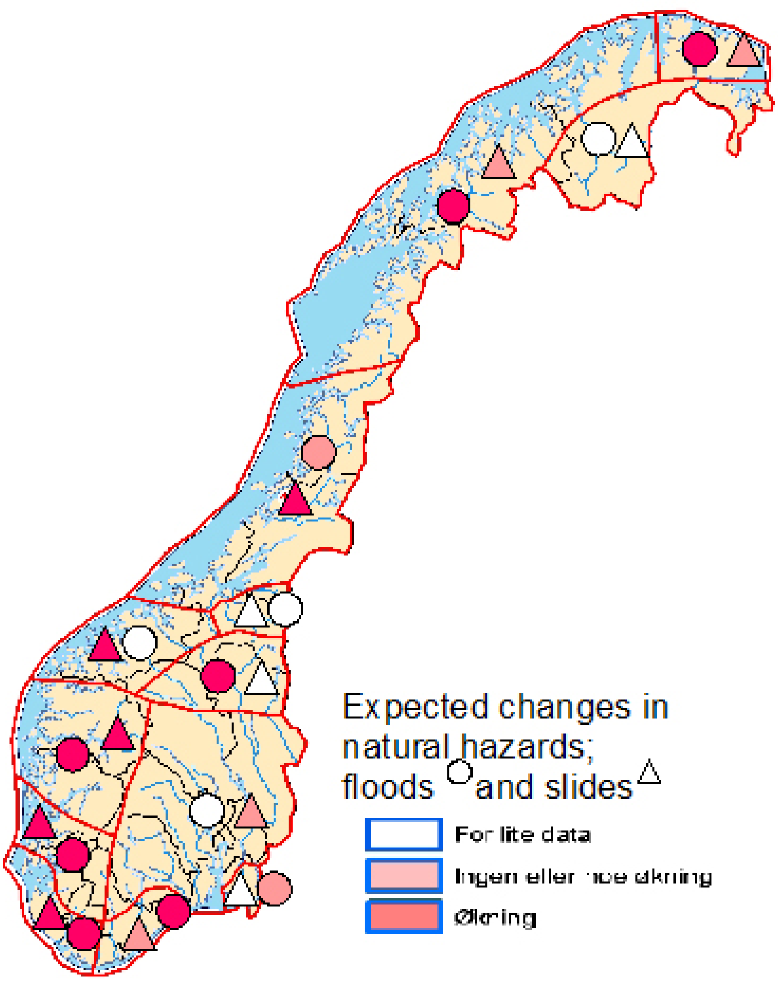


Figure 10.6 Expected changes in natural hazards, by precipitation region, annual average.

The map shows the average annual changes in slides and flooding in the thirteen precipitation regions identified by RegClim. Seasonal changes are expected for all natural hazards. This is described in more detail in the previous chapters. The map shows that slides are expected to increase in western Norway and parts of northern Norway. Southern and western Norway, and coastal areas in the north, can expect an increase in flooding. The map shows that there is considerable uncertainty associated with the expected changes for these natural hazards, and for many regions there is too much uncertainty or too little available data to allow us to draw any conclusions about changes in natural hazards.

10.3 Conclusion

The data on assessed costs from natural damage provided by SLF show that until now flooding has caused the damage with the highest costs in Norway. It is expected that climate change will lead to increased precipitation, which in turn can lead to increased flooding, but that there will also be seasonal changes in the patterns of flooding in Norway. There is considerable uncertainty regarding where and when natural hazards will occur, and whether new and additional areas will be more at risk. But the analyses also show that there will be a clear increase in winter flooding in Finnmark and in eastern Norway. Until now, the assessed costs from natural damage caused by flooding have been high in eastern Norway, and with an increase in winter flooding in Finnmark, we can expect a higher extent of damage in this region. When it comes to slides, an increase in land- and mudslides is expected along the coast, especially in western and northern regions, and an increased magnitude of damage from these events. Buskerud, however, which has until now had high assessed damage costs, is not expected to experience any change in the frequency or scope of damage.

The analyses at the regional level give some indications of expected trends, but we do not have detailed enough information to say with certainty where the vulnerability will be greatest, and to which natural hazards. Generally speaking, the climate scenarios provide a clear indication that we can expect an increased frequency in all types of weather that trigger natural hazards.

To say more about vulnerability to natural hazards, the information must be connected to demographics and economics at a relatively local level, such as the municipal. There is not necessarily a correlation between high assessed costs and the magnitude of the natural hazard; a major natural hazard (such as an avalanche) in an area with little infrastructure and few buildings can have an assessed damage cost that is low or even zero, while a smaller natural hazard in a densely populated area can have high assessed damage costs. It is important to take into consideration which areas can be exposed to natural hazards when new housing developments and roads are planned.

What will be important, given the knowledge that we have about an increase in natural hazards in the time to come, is to adapt society such that the scope of damage is kept to a minimum. Knowledge and research in this area must be developed if Norway is to have the opportunity to adapt to both expected and unexpected climate change and the resulting natural hazards. Where the infrastructure is not adapted, the damage from natural hazards can be greater. The «Vesle Ofsen» flood in 1995 is an example of how a single incident can have high costs. Many hazards occur so seldom that protective measures or adaptation to these have not been carried out, which can mean that the damage will be that much more extensive when the natural hazard actually occurs. Investment in protection, good land-use planning, and good building practices are all important elements to limit the damage from natural hazards.

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Appendix 1: Definitions for chapters 3 & 4

Flood event
A flood will normally cover a connected geographical area, and will be caused by the same weather system a primary condition within this area. One event can affect several rivers or districts, usually with a core area, with a less affected outer area. Flood events have been identified by considering both the geographical, temporal and causative factors, in order to define independent events which form the basis for the Norwegian Flood Database. Some events such as the major floods covering large areas with several core areas or long-duration floods such as the almost 3 month long autumn flood in 2000 along the Oslofjord, can be divided into sub-events.

Flood severity
The severity of a flood event has been classified into one of four classes. Recent floods can be classified according to the return period, but this is not a useful measure in regulated rivers, where the flood magnitude depends on the operation of the hydropower system, which may have changed over time. It is neither useful in classifying floods prior to the instrumental period. The classification is instead based on subjective criteria, such as the flood level, where known, the geographical extent of the event, the damages and losses of life as known from documentary sources.

The classes are:

1. ***Ordinary floods:*** Annual flood exceeding a subjective limit based on ranking of the floods as well as the damage and geographical extent.
2. ***Large floods:*** The no 2 or 3 largest floods in a fairly long series. The ranking is based on naturalised floods in regulated rivers.
3. ***Severe floods:*** Floods causing severe damage and/ or appear as large outliers in the observed flood series.
4. ***Extreme floods:*** The largest most disastrous floods causing extreme damage and usually loss of lives. (Only 12 out of 700 events have been classified as extreme).

Frazil ice and dynamic ice formation
Frazil ice is very small floating ice particles formed be freezing of super-cooled water. As long the ice crystals stay super-cooled the frazil is active and will freeze on any subject. In turbulent water the frazil will form bottom ice when it hits the river bottom. Some places the frazil ice will form bottom ice dams. Upstream dams formed by bottom ice the water velocity decreases and an ice cover will form. This is called dynamic ice formation.

Thermal ice release
The ice cover will weaken due to positive air temperatures in the spring. With a gradual increase in temperature the ice cover will normally more or less melt on the spot. The water stage increases normally slowly. This is called thermal ice release.

Ice runs and ice jams
With increasing water stage the ice level will also increase, and the ice cover will start floating. If the water stage keeps increasing sufficiently, the whole ice cover will break up and start floating downstream. This is an ice run. When the floating ice meets obstacles, such as narrows and bends in the river or shallow areas etc, the ice will pile up and start jamming. Eventually the ice will move down the river, shifting between local ice-runs and jammed areas.

Weather types
The spatial distribution of high and low pressure areas as well as dominant wind systems have been classified from weather maps by Lamb (1972) for conditions focused on the UK and by Hess & Brezowsky (Gerstergarbe & Werner, 2005). The classification by Lamb operate with 27 classes of daily weather type covering the period 1861–1971, while the Hess & Brezowsky classification starts in 1881, is focused on Germany and operates with 30 classes. Objective methods of classification have later been developed (Hulme & Barrow, 1997). Heavy rainfall and flood events in tend to occur for groups of similar weather types in different regions of Norway, although the classification is focussed at locations elsewhere.

Appendix 2: Overview of some historical floods

Table A.1 Overview of some large spring and early summer floods in some major rivers

Year	Peak date	Water courses
1675	28th May	Glomma/Gaula/Otra
1760	29th May	Glomma and Lågen
1773	29th–30th May	Glomma especially in Østerdalen/Glåmdalen
1846	24th–26th May	Glomma in Østerdalen/Glåmdalen/Drammenselva/Skienselva/Driva
1850	27th May – 18th June	Glomma/Vorma
1853	3rd–5th June	Drammenselva
1860	15th–22th June	Nedre Glomma/Lågen/Drammenselva/Numedalslågen/ Skienselva/Sima/ Lærdøla/Årdalselv/Driva
1879	May – June	Numedalslågen/Skienselv/Geirangerelv/Driva/Surna/Orkla/ Gaula
1897	27th May –7th June	Lågen/Tyrifjorden/Ådalselv/Begna/Krøderen/Numedalslågen/Skienselv/ Bøelv/Otra/Lærdalselv
1910	25th–28th May	Nedre Glomma/Randsfjorden/Begna
1916	11th–16th May	Glomma/Drammenselv/Numedalslågen/Skienselv/Nidelva (Trøndelag)
1920	20th–23th May	Begna/Lærdalselv/Alta/Tana/Neiden/Pasvik
1934	6th–19th May	Glomma/Drammenselv/Numedalslågen/Skienselv/Nidelv/Otra/ Stryn/ Surna/Driva/Orkla/Gaula/Nidelv/Stjørdalselv/Vefsna
1966	19th–21st May	Glomma/Drammenselv/Numedalslågen
1967	29th May – 3rd July	Klara/Glomma except Jotunheimen/Begna/Hallingdalselv/
1995	29th May – 12th June	Glomma except Jotunheimen/Drammenselva/Driva/Gaula/ Nidelva/ Stjørdalselv/Fusta
1996	10th June	Tana/Neiden

Table A.2 Overview of some large mountain floods in South and Central Norway

Year	Peak date	Water courses
1755		Bøvra
1822	25th April	Rådåå at Dovre
1826	11th July	Aurlandselv/Tya/Utla/Fardøla/Lærdøla
1895	Aug.	Skjøli at Skjåk
1914	6th–8th July	Usta/Bjoreio/Aurlandselv/Tya/Utla/Oldeelva
1932	7th– 8th July	Jora/Otta/Sjoa/Vinstra/Eira/Litledalselv/Driva
1958	26th June – 3rd July	Usta/Austdøla/Veig/Bjoreio/AurlandselvGlomma/Nøra/ Folla/Otta/Vinstra/ Rauma
1968	2th–4th July	Otta/Bøvra/Sula/Visa/Høya/Skjøli/Tundra/Ostri/Tora/ Aurlandselv/ Strynselv/Rauma
1972	6th–8th June	Vinstra/Sjoa/Otta/Bøvra/Jora
1973	7th–9th July	Sjoa/Otta/Bøvra/Veig/Jostedøla/Oldeelva
1985	1st–2nd Oct.	Tributaries to upper Otta/Breimselv/Strynselv/Nausta/Oldeelv/ Bygdaelva
1995	21st July	Rivers on the western side of Hardangervidda i.e. Suldalslågen/ Austdøla/ Opo
2004	6th May	Måna/Bøvra/Leira/Rudiåa in Dovre

Table A3 Overview of some large autumn and early winter floods in West and North Norway (continues on next page)

Year	Peak date	Water courses
1702	26th–28th Oct.	Hjelledøla in Oppstryn
1723	Autumn	Hardanger
1742	7th Dec.	Olden
1743	4th–5th Dec.	Ryfylke-Nordmøre
1743	20th Dec.	Coastal rivers Hordaland-Sunnfjord
1745	Autumn	Vosso
1756	14th–22th Feb	Langfjorden/Surna

Table A3 Overview of some large autumn/winter floods in West and Mid Norway (cont.)

Year	Peak date	Water courses
1812	21st Sep.	Vosso
1842	15th–16th Oct.	Valldøla/Usma
1873	9th Dec.	Vosso
1881	27th Dec.	Høyangerelv/Daleelv
1883	7th–10th Oct.	Valldøla
1884	1st Nov.	Granvinelv/Vosso
1888	27th–29th Oct.	Granvinelv/Vosso
1899	18th Oct.	Vosso
1906	22nd–24th Nov	Årdalselv/Lærdøla/Gaular/Jølstra/Breimselv/Langedøla/ Bygdaelva
1913	18th–24th Oct.	Årdalselv – Breimselv/Langedøla/Bygdaelva
1917	27th–30th Sep.	Ryfylke/Hardanger/Gaular/Jølstra/Eidselva
1918	10th–11th Oct.	Vosso/Eksingsdalselv
1932	28th–29th Jan.	Sunnfjord – Fosen
1934	28th Nov.	Nord-Hordaland/Sunnfjord
1940	24th–27th Nov.	Ryfylke – Sunnfjord
1953	10th–11th Oct.	Coastal basin at the Bergen Peninsula
1956	22th Oct.	Ulla – Sunnmøre
1957	9th Jan.	Coastal basins from Sogn - Fosen
1971	2nd–3rd Nov.	Vosso/Høyangerelv/Gjengedalselv
1983	26th Oct. - 1st Nov.	West Norway
2006	30th Jan. – 1st Feb.	Trøndelag especially Fosen

Table A4 Overview of some widespread rainfall floods

Year	Peak date	Water courses
1719	13th Aug.	Vosso
1752	23rd Aug.	Tinne/Måna
1789	21st–23rd July	Klara/Glomma/Drammenselv/Skienselv/Nidelva/Driva/Surna/Orkla/Gaula/
1822	Aug.	Krøderen/Skienselva
1858	July	Snarumselva/Tinne/Måna
1892	8th–9th Oct.	Simoa/Numedalslågen/Skienselva
1909	14th Aug.	Driva/Todalselv/Gaula/Nidelva/Stjørdalselva
1927	27th June – 2nd July	Lågen/Drammenselv/Numedalslågen/Skienselv
1934	4th– 7th Aug.	Lower Drammenselv/Skienselv
1938	29th Aug. – 2nd Sep.	Gudbrandsdalslågen/Otta/Skienselv
1966	7th–8th Sep.	Coastal basins Ryfylke - Sunnfjord
2003	14th–15th Aug.	Isa/Eira/Driva/Todalselv/Surna/Stjørna
2005	13th–14th Sep.	Hordaland
2005	14th Nov.	Hordaland

Table A5 Overview of some local flash floods

Year	Peak date	Water courses
1662	8th Sep.	Jølstra (local rainflood)
1686	8th Sep.	Jølstra (local rainflood)
1763	21st–22nd Aug.	Røldal
1876	14th June	Svarteberglien and Nersetlien at Ål
1896	14th–15th Aug.	Kragerøelv/Gjerstadelv/Vegårdselv
1953	10th–11th Oct.	Oselv/Samnanger
1986	6th Aug.	Notodden
2004	27th Aug.	Ørsta/Vanylven
2006	30th Aug.	East of Garmo, near the border towards Vågå

Table A6 Floods linked to ice runs

Year	Peak date	Water courses
1683	28th May	Glomma at Storelvdal
1691		Glomma at Stai
1717	24th May	Glomma at Storelvdal
1828		Imsa
1850		Gaula
1854-1855		Orkla
1880		Driva
1881	25th–27th Dec.	Driva/Orkla
1882	18th Jan., 25th Jan., 16thMar.	Driva
1925–1931		Glomma at Koppangsøyene
1926		Glomma at Stai
1953	25th– 26th Mar.	Orkla/Gaula
1962	3rd–6th Dec.	Namsen

Table A7 Overview of some floods caused by glaciers

Year	Peak date	Water courses
1741	14th Aug.	Jostedalen/Vetlebreen
1742	7th Dec.	Olden
1743	12th Dec.	Olden
1804		Olden at River Tverrelven
1805	18th Sep.	Olden at River Tverrelven
1842		Simadalen
1849	19th Feb.	Lausavatn in Hardanger
1861	17th Sep.	Simadalen
1895 1897	End of July	Brimkjelen in Jostedal
1897	17th Feb.	Simadalen
1899	End of July	Brimkjelen in Jostedal
1926		Brimkjelen in Jostedal
1937	10th Aug.	Simadalen
1938	23rd Aug.	Simadalen
1941	14th July	Olden/Loen
1966	7th–8th Sept.	Folgefonni/Fjærland/Nordalselv/Riseelv
1971	25th–26th Aug.	Engabreelv/Rana
1979	14th–15th Aug.	Fjærland/Jostedalen
1997	30th Aug.	Jostedalen/Olden
2001	6th Sep.	Blåmannsisen
2004	6.- 8. May	Leira (Bøverdal)/Suphellerelv
2005	29. Aug.	Blåmannsisen