World Geomorphological Landscapes

Achim A. Beylich *Editor*

Landscapes and Landforms of Norway

Springer

World Geomorphological Landscapes

Series Editor

Piotr Migoń, Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland

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Solen/The Sun Edvard Munch 1910–13

Nord

Se oftere mot nord.
Gå mot vinden, du får rødere kinn.
Finn den ulente stien. Hold den.
Den er kortere.
Nord er best.
Vinterens flammehimmel, sommer-
nattens solmirakel.
Gå mot vinden. Klyv berg.
Se mot nord.
Oftere.
Det er langt dette landet.
Det meste er nord.

Rolf Jacobsen, Nattåpent, Gyldendal Oslo, 1985

North

Look more often towards the North.
Go against the wind, you get redder cheeks.
Find the rugged trail. Hold it.
It is shorter.
North is the best.
Winter's flaming sky, summer-
night sun miracle.
Go against the wind. Climb the mountain.
Look to the North.
More often.
This country is vast.
Most of it is North.

Rolf Jacobsen, Nattåpent, Gyldendal Oslo, 1985
(translated from Norwegian to English)

Preface

“Geomorphology is the interdisciplinary study of landforms, their landscapes and the earth surface processes that create and change them” (International Association of Geomorphologists 2019).

Mainland Norway stands for a great variety of beautiful and spectacular landscapes with these landscapes being a function of geological and geomorphological processes working over very long time spans and under varying climates. The outstanding beauty of the Norwegian nature has been an inspiration for famous Norwegian artists, e.g., the painter Edvard Munch (1863–1944), the poet Rolf Jacobsen (1907–1994) and the composer and pianist Edvard Grieg (1843–1907).

Building on the large body of existing literature on the long-term geological and Quaternary geological development of the Norwegian landscapes, the purpose of this book is to provide the first compilation of selected geomorphological review works and in-depth studies on relevant geomorphological earth surface processes and the resulting modification of landscapes and/or creation of new landforms and landscapes. The book shall contribute to filling a still existing gap regarding the in-depth understanding of Holocene, and particularly of contemporary geomorphological earth surface processes and how these processes change existing landforms and landscapes and/or create new landforms and landscapes. An improved scientific in-depth understanding of the mechanisms and drivers of geomorphological earth surface processes and their resulting landforms and/or landform and landscape changes is of utmost importance with respect to urgently needed qualified assessments of the possible geomorphological effects of ongoing and accelerated environmental changes, and in view of the increasing importance of the efficient development of geo-hazard assessment applications. Also, the status and value of geomorphological heritage are addressed with selected examples from different key landscapes in mainland Norway. All accepted chapters of this book are well illustrated with numerous figures and photographs and shall, also for non-academic readers, increase the awareness of the outstanding beauty, the increasing vulnerability and the hazardous potential of the various landscapes of mainland Norway.

The preparation of this book on Landscapes and Landforms of Norway would not have been possible without the very valuable work of the selected expert reviewers. The work and contributions of the invited chapter authors and the selected expert reviewers are greatly acknowledged. I also would like to thank the Book Series editor Piotr Migoń and Michael Leuchner, Robert Doe, Manjula Saravanan and Banu Dhayalan of Springer Nature Verlag for their support during the preparation and publishing process of this book.

Selbustrand, Norway
September 2019

Achim A. Beylich

Reference

International Association of Geomorphologists (2019) http://www.geomorph.org (September 2019)

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About the Editor

Achim A. Beylich (Geomorphological Field Laboratory (GFL), Sandviksgjerde, Strandvegen 484, 7584 Selbustrand, Norway) is a geomorphologist with more than 25 years of work experience in field- and laboratory-based quantitative process geomorphic research in various climatic environments and landscapes in Iceland, Sweden, Finland, Canada, Russia, Germany, Austria, Norway and Spain. Since 2004, he has been initiating and leading a number of large international and interdisciplinary research groups, networks and programs on geomorphologic earth surface processes and landscape development under ongoing or accelerated climate change and increasing anthropogenic impacts and pressures. During his scientific career, he has carried out research and has been working at research institutes and universities in Germany, Sweden, Iceland, Canada and Norway, and he is currently Head of Operations at the Geomorphological Field Laboratory (GFL) in Selbustrand, Norway. He is a senior scientist with more than 100 scientific publications in journals and books, numerous edited works and with formal full professor competence in geomorphology. He is Editor-in-Chief for the scientific journal *Geomorphology* (Elsevier), an Editorial Board Member for several international scientific journals, and serves frequently as a peer-reviewer for a number of international scientific journals and for various national and international funding bodies and agencies. He is the President of the IAG Geomorphological Research Group of Norway (IAG GeoNor), initiator and Chair of the Nordic IAG Network of National Geomorphology Groups from Norway, Sweden, Finland, Denmark and Iceland (IAG GeoNorth), and the Norwegian National Scientific Representative (IAG National Scientific Member Norway) for the International Association of Geomorphologists (IAG).

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Part I

Introduction to Landscapes and Landforms of Norway

1 Geomorphological Landscapes, Earth Surface Processes and Landforms in Norway

Achim A. Beylich

Abstract

Mainland Norway stands for a great variety of partly spectacular landscapes with these landscapes being a function of geological and geomorphological processes working over very long time spans. Building on the large body of existing literature on the long-term geological and Quaternary geological development of the Norwegian landscape, the purpose of this book is to provide the first compilation of selected review works and geomorphological in-depth studies on relevant geomorphological earth surface processes and the resulting modification of existing and/or creation of new landforms. The book shall contribute to filling a still existing gap regarding the in-depth understanding of Holocene, and particularly of contemporary geomorphological earth surface processes and how these processes change existing landscapes and landforms and/or create new landforms. The review works and geomorphological in-depth studies selected for this book cover a range of varied geomorphological key landscapes, earth surface processes and landforms in mainland Norway. An improved scientific in-depth understanding of the key drivers, mechanisms, spatiotemporal variability and quantitative rates of contemporary geomorphological earth surface processes and of their resulting landforms and/or landscape and landform changes is of utmost importance with respect to urgently needed qualified assessments of the possible geomorphological effects of ongoing and accelerated environmental changes and in view of the increasing importance of the efficient development of geo-hazard assessment applications. Also, the status and value of geomorphological heritage are addressed with selected examples from different key landscapes of mainland Norway.

Keywords

Landscapes • Landforms • Geomorphological earth surface processes • Environmental changes • Geo-hazards • Geomorphological heritage • Mainland Norway

1.1 Introduction

Norway stands for a great variety of partly spectacular landscapes with these landscapes being a function of geological and geomorphological processes working over very long lime spans. There is a large body of existing literature explaining in great detail the geological and Quaternary geological long-term development of the Norwegian landscapes, including the major key compilations on *The Making of a Land—Geology of Norway* edited by Ramberg et al. (2008) and *Quaternary Geology of Norway* edited by Olsen et al. (2013). Distinct first-order structures of the present Norwegian landscape can be traced back to ancient denudational processes, the Caledonian orogeny or break-up of the North Atlantic, whereas a large portion of today's large-, intermediate- and small-scale landforms in Norway were created by earth surface processes operating during the Quaternary time period, and mostly by the action of glaciers through numerous glaciations (e.g. Fredin et al. 2013; Olsen et al. 2013). The Quaternary time period, comprising the last ca. 3 million years, is characterized by cool and variable climate with temperatures oscillating between relative mildness to frigid ice-age conditions. Fredin et al. (2013) summarize that the numerous glaciations during the Quaternary "have had the most profound effect with the production of large U-shaped valleys, fjords and Alpine relief. On the other hand, interior and upland areas in Norway seem to be largely unaffected by glacial erosion and exhibit a possibly pre-Quaternary landscape with only some periglacial influence. The ice sheets in Scandinavia thus have

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redistributed rock mass and sediments in the landscape with the largest glaciogenic deposits being found on the continental shelf. Large Quaternary deposits and valley fills can also be found onshore and these are now valuable resources for aggregates, ground water and agriculture. Important Quaternary processes have also been acting along the Norwegian coast with denudation of the famous strandflat, where the formation processes are not fully understood. The isostatic depression of crust under the vast ice sheets have also lead to important consequences, with thick deposits of potentially unstable, fine-grained glaciomarine sediments in quite large areas of Norway" (Fredin et al. 2013).

1.2 Geomorphological Earth Surface Processes and Resulting Landforms

"Geomorphology is the interdisciplinary study of landforms, their landscapes and the earth surface processes that create and change them" (International Association of Geomorphologists 2020). Building on the large body of existing literature on the long-term geological and Quaternary geological development of the Norwegian landscape, the purpose of this book is to provide the first compilation of selected review works and geomorphological in-depth studies on relevant geomorphological earth surface processes and the resulting modification of existing and/or creation of new landforms. The various scientific contributions of this book include review works and geomorphological in-depth studies on glacial, periglacial, and denudational hill slope and fluvial processes, and explain in detail (i) the mechanisms, controls, quantitative rates as well as (ii) the modification of existing landscapes and landforms and the creation of new landforms resulting from these varied earth surface processes. While highlighting the advanced existing knowledge on the geology and Quaternary geology of mainland Norway, this book shall contribute to filling a still existing gap regarding the in-depth understanding of Holocene, and particularly of contemporary geomorphological earth surface processes and how these processes change existing landscapes and landforms and/or create new landforms and landscapes. An improved scientific in-depth understanding of the key drivers, mechanisms, spatiotemporal variability and quantitative rates of contemporary geomorphological earth surface processes and of their resulting landforms and/or landscape and landform changes is of utmost importance with respect to urgently needed qualified assessments of the possible geomorphological effects of ongoing and accelerated environmental changes and in view of the increasing importance of the efficient development of geo-hazard assessment applications.

1.3 Geomorphological Study Regions and Landscapes Presented in This Book

Following the introductory part of this book (book part I with this chapter and book chapter 2, including a brief general introduction to geomorphological landscapes, earth surface processes and landforms in Norway (this chapter), and a detailed overview of the climate of mainland Norway and geomorphologically relevant aspects of the contemporary climate (Ketzler et al. 2021), the geomorphological review works and in-depth studies selected for this book (book part II with book Chaps. 3–10) cover a range of varied geomorphological key landscapes, earth surface processes and landforms across mainland Norway (Fig. 1.1). In book part III (book Chaps. 11 and 12), the status and value of geomorphological heritage in Norway are addressed with selected examples from different key landscapes of mainland Norway (Fig. 1.1).

In book part II, the book Chaps. 3–7 focus on the magnificent Jostedalsbreen ice cap and the steep and spectacular fjord landscapelandscape in south-western Norway (Fig. 1.1). In book Chap. 3 (Winkler 2021), terminal moraine formation processes and the geomorphology of glacier forelands at selected outlet glaciers of the Jostedalsbreen ice cap are presented, whereas contemporary ice retreat and the associated formation and changes of proglacial lakes at this impressive ice cap are the topics of book Chap. 4 (Laute and Beylich 2021). In book Chap. 5 (Curry 2021), paraglacial rock-slope failures following deglaciation in rock-slope mountain landscapes in western Norway are discussed in detail. Snow-avalanche impact landforms in western Norway are explained and discussed in book Chap. 6 (Matthews and Owen 2021), whereas fluvial processes and contemporary fluvial denudation in the different glacierized and non-glacierized mountainous landscapes of western and central Norway (Fig. 1.1) are the topics of book Chap. 7 (Beylich and Laute 2021). Book Chap. 8 (Winkler et al. 2021) presents and discusses periglacial processes and landforms in the Alpine mountain landscape of Jotunheimen in central southern Norway (Fig. 1.1). The mountainous landscape of Rondane in south-central Norway (Fig. 1.1) is in the focus of book Chap. 9 (Sellier and Kerguillec 2021a) with the characterization and the explanation of the significance of scree slopes investigated in this region. The morphological description of erosional and depositional landforms created by debris flow processes is

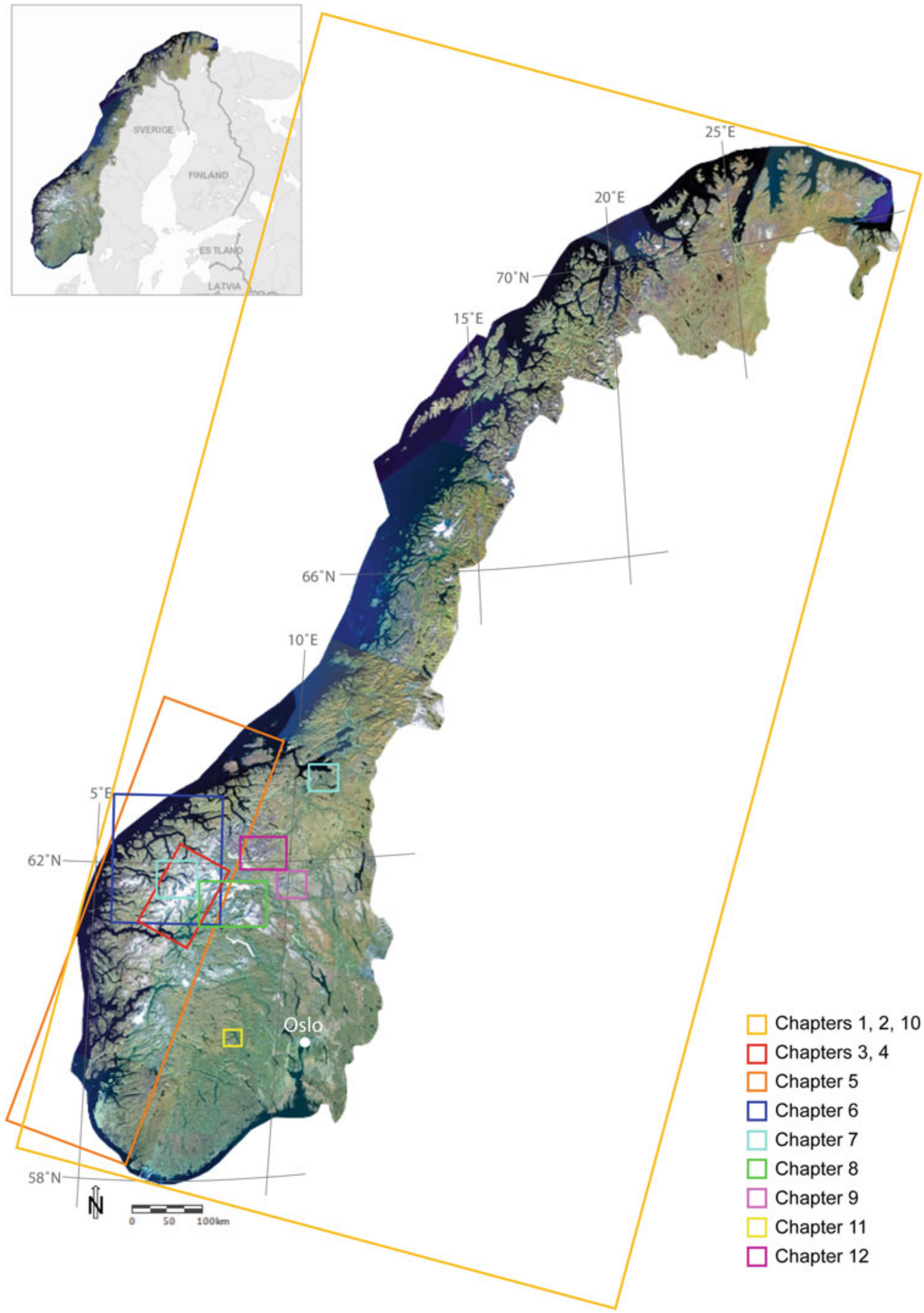

Fig. 1.1 Location of the selected study regions and geomorphological landscapes presented in the 12 chapters of this book. *Source* of Norway map and inset ©NVE Atlas 3.0 (Kartverket, Geovekst og kommuner-Geodata AS, NVE)

presented and discussed in book Chap. 10 (Rubensdotter et al. 2021) with examples from different selected mountain regions across mainland Norway (Fig. 1.1). In book part III, landforms and geomorphosite designation on Mount Gausta in Telemark (Fig. 1.1) are described and discussed in detail in book Chap. 11 (Sellier and Kerguillec 2021b), whereas the selection of geomorphosites in the mountainous upland landscape of the Dovrefjell and Sunndalsfjella National Park in central Norway (Fig. 1.1) is the focus of the final book Chap. 12 (Kerguillec and Sellier 2021).

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2 The Climate of Norway

Gunnar Ketzler, Wolfgang Römer, and Achim A. Beylich

Abstract

Mainland Norway shows a complex combination of physical factors leading to various climate settings. Due to the huge extension in north–south direction from 57° 58′ N to 71° 11′ N, Norway encompasses five climate zones according to the Köppen classification. Its location on the west side of the Scandinavian Peninsular close to the North Atlantic Current, however, shifts most climate effects to a more temperate level compared to what is to expect from the given geographical zone. Especially during the last two decades, a marked temperature increase is observed over the whole country. The close interlink with sea climates due to the very long coastline with many fjords and islands, effects of altitude as well as of luv and lee situations of different mountainous regions up to 2469 m a.s.l. and the general west–east gradient from maritime to continental climates result in various patterns of climate elements on a regional and local scale. Southwest Norwegian coastal lowlands have a quite temperate climate and the mountainous areas situated behind often show huge amounts of precipitation during all seasons including partly enormous snow accumulation in winter supplying numerous glaciers. The more continental areas of Eastern Norway are very dry, and the elevated mountain plateaus, especially in Northern Norway, are of subarctic appearance including phenomena of permafrost.

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Keywords

Solar radiation • Temperature • Precipitation • Wind • Topoclimate

2.1 Introduction

This chapter aims at giving an overview of the main climate factors influencing geomorphological processes and their geographical distribution. This also includes general statements, but it is not intended to outline a complete climatology of Norway but rather an overview of regional morphoclimatology.

By doing so, we generally follow the morphoclimatological approach of Ahnert (e.g. 1987). This approach has the intention to focus on those climatic conditions and processes relevant for morphological processes and to quantify as far as reasonable the relation between their magnitude and their frequency. An example of a field study from Norway based on morphoclimatic analysis is given by Beylich and Laute (2018). For the present—in a spatial and functional sense—more general study, extensive quantification, e.g. in the form of detailed analysis of frequency distributions, is not performed, but, however, it is intended to discuss the most important aspects of a morphoclimate on the basis of figures describing intensity and temporal dimension.

There are few surveys on the climate of Norway or Scandinavia in international publications. Williams (1901) already gives an overview of the main patterns caused by the North Atlantic Current and the country's situation in relation to mountain ranges, already taking into account the results of early meteorological measurements. Johanessen (1970) extensively documents and discusses the—at that time—already large extent of data from numerous stations in Norway with a scope on complete Scandinavia, beginning to analyse newer data series like solar radiation. Norseth (1987) continues this work focussing on the annual radiation deficit and

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its compensation by large-scale advection of (latent) heat including the role of atmospheric circulation types and interaction with the hydrological cycle. Tikkanen (2005), too, underlines the role of circulation types, introduces topoclimatological effects in the regional climatology of Norway and Scandinavia and—in this context—points to local climate extremes like extreme precipitation data from newer measurements and modelling activities.

After a short overview over the general setting and Norway's specific location, this chapter on the morphoclimate of Norway focusses on fundamental astronomical conditions for and virtual input of solar radiation, followed by a review on spatial distribution and frequency of average and extreme temperature and precipitation data including a closer view on effects of the adjacent marine areas on temperature and humidity. A section on wind conditions is added. Regional and topoclimate features and expected effects of climate change are discussed afterwards.

Norway's location on the west side of the Scandinavian Peninsula in north-western Europe between 57° 58′ N and 71° 11′ N respectively 4° 40′ E and 30° 58′ E (from Kartverket 2018) indicates a central position in the westerlies and a classification as part of both the temperate and polar climate zones. It forms an elongated territory on the west and partly on both sides of Scandes (see Fig. 2.1), with an extension of about 1700 km from the southernmost point Cape Lindesnes to the North Cape having a very long and structured coastline as well as mountain areas with an altitude of up to 2469 m a.s.l. (Galdhøppigen). The country has—in relation to other western European countries—a remarkable N-S-extension of 13° 13′ or 1470 km, but its E-W extension (26° 18′ = 1160 km based on the latitude of the northern polar circle) is also not negligible although this fact usually attracts little attention.

2.2 Solar Radiation

The energy for atmospheric and geomorphologic processes originally comes from solar irradiation. Being located between latitudes of 58.0°–71.2° N, Norway is characterized by marked differences in the solar climatic conditions. These differences are indicated in the strongly differing day length at the summer and winter solstices. At a latitude of 58° N, the longest and shortest days are experiencing 18:11–6:10 h daylight, at 60° N the daylight ranges from 18:53 to 5:52 h, at 63° N the daylight ranges from 20:19 to 4.42 h and at the Arctic Circle (66.5° N) the longest daytime is 24 h whilst the shortest day has 0 h, when twilight is excluded. During the summer, the northernmost regions experience a period of more than 2 months with daylight whilst in the winter a period of about 2 months with night (Tikkanen 2005). In the winter months, the high latitudes receive no direct solar radiation, though the astronomical twilight resulting from refraction and reflection of sunrays produces twilight until the sun is 18° below the horizon.

At the summer solstice at 58° N (e.g. Kristiansand), 60° N (e.g. Bergen and Gardermoen) and 63° N (e.g. Trondheim/Værnes), the sun's angle of incidence decreases from 55.5° to 53.5° and 50.5. At the Arctic Circle at the summer solstice, the sun's angle of incidence is never higher than 47.9° and at the northernmost point of Norway at the latitude of 71.2° N the maximum angle of incidence is 42.1°. This angle of solar incidence corresponds with an angle of incidence at the equinoxes at the latitude of 48°. For latitudes 71° N and 58° N, the ratio of the spread of solar radiation over a horizontal area is 0.81 (=sin 42.5°/sin 55.5°) at the summer solstice and appears to indicate only minor differences in the influx of solar energy. However, the ratio decreases markedly during the equinoxes to 0.61 and diminishes to zero in the winter months. When considering the influence of day length and the angle of incidence, the differences in the solar irradiation become even more pronounced. On 21 December, 21 March (23 Sept) and 21 June, the solar irradiation at 70° N attains 0 W m^{-2}, 149 W m^{-2} (147 W m^{-2}) and 492 W m^{-2} whilst at 50° N solar irradiation increases from 86 W m^{-2}, 280 W m^{-2} (276 W m^{-2}) to 482 W m^{-2}. Over a year, the summed solar energy attains 1768 kWh m^{-2} at 70° N, 2123 kWh m^{-2} at 60° N and 2559 kWh m^{-2} at 50° N (Weischet and Endlicher 2012). Thus, as a result of the northern location the intensity of solar radiation in Norway is never very high but in summer the sum of global radiation even in Northern Norway nearly equals the figure for 50° N.

However, on average solar intensity decreases towards the north as a function of decreasing angle of incidence, being modified by cloudiness, aerosols and relief. In the summer months, the duration of solar radiation increases northward and part of the energy is consumed for melting snow and ice and evaporating water. Although the astronomic sunshine hours increase from 4500 h a^{-1} at 62° N to 4600 h a^{-1} at 70° N, there is a decrease in the average daily global radiation of 8280 kJ m^{-2} at 63° N to about 6400 kJ m^{-2} at 69° N (Johanessen 1970). Accordingly, the energy deficit increases northwards from 1670 MJ m^{-2} at a latitude of 55° N to about 2800 MJ m^{-2} at a latitude of 70° N (Johanessen 1970: 25). The northward increase in the annual energy deficit is partly compensated by the release of latent heat by condensation and advection of air from southerly latitudes and by heat from the North Atlantic Ocean (Norseth 1987). However, the simple radiation tendencies are modified by several factors. The solar irradiance not only decreases northwards but also towards the west (Skartveit and Olseth 1986). As Norway is located in the zone of westerly winds, the increase in elevation along the Norwegian coast forces the rise of moist air masses. This results in an increase in cloudiness and precipitation along the coastal areas, which is indicated, in particular, at the

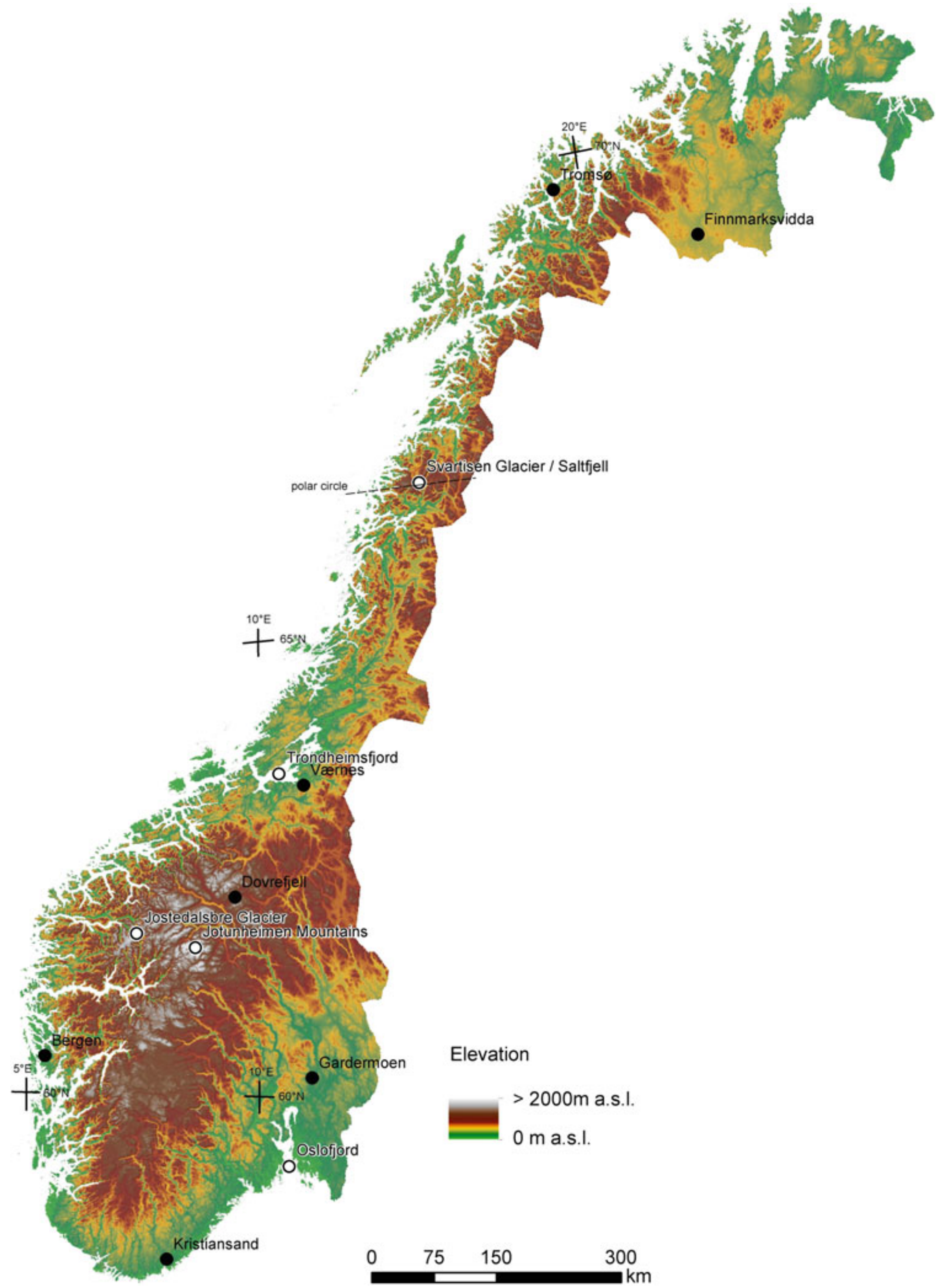


Fig. 2.1 Norway—general location and elevation; additionally weather station sites and other places referred to in the text (*Data source* NMI 2018a)

south-western coast of Norway, where the mean annual irradiance is markedly decreased by the high cloudiness (Skartveit and Olseth 1986).

The actual input of solar radiation (SR) at surface level is controlled by real combination of the factors mentioned above. As direct measurements of SR were generally rare during the last regular climatological normal period (1961–1990), data of sunshine duration (SD) were used here to analyse regional differences of such combinations. Nevertheless, these data give additional information for geomorphological processes as SD is defined as solar irradiance (SI) with an at least considerable intensity (minimum 120 W/m^2) and relative to a surface perpendicular to the beam of sunlight (WMO 2008). As horizontal surfaces, which are the reference for other SR measurements, are an exception in mountainous areas, SD data may give a realistic impression on the possible frequency of considerable solar energy input on mountain surfaces.

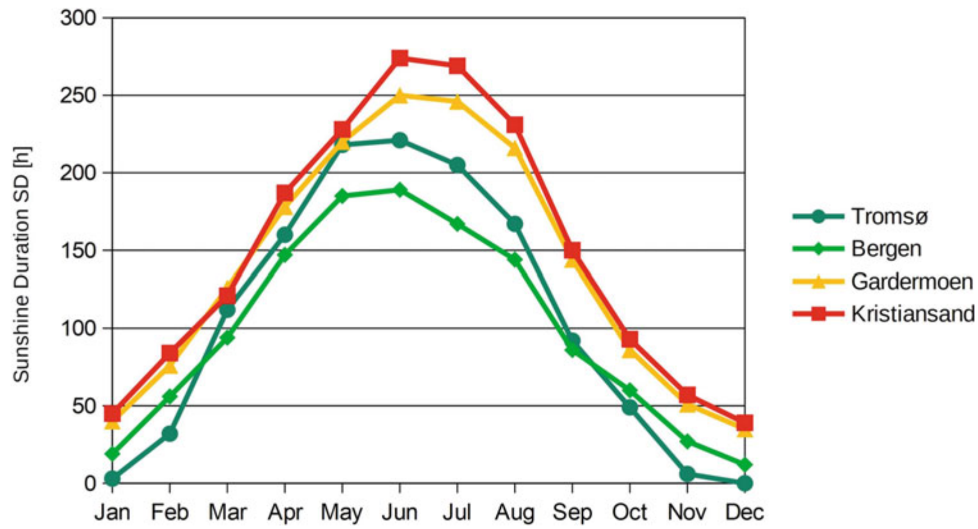


Fig. 2.2 Monthly sunshine duration at four Norwegian stations 1961–1990 (*Data source* NMI 2018b)

A general increase in sunshine duration according to latitude can be seen in Fig. 2.2. The monthly values of SD for the Southern Norwegian places Kristiansand (station Kjevik, 64° 73′ N; station locations see Fig. 2.1) and Gardermoen (66° 48′ N) are generally higher than for Tromsø (77° 19′ N; all station data from NMI 2018b). In the months around winter solstice (November, December and January), the places north of the arctic circle virtually receive no sunshine and only diffuse sky radiation according to the astronomical conditions. In the months of March to May, the SD values for North Norwegian Tromsø nearly equal those of Kristiansand (about 1400 km southward) or Gardermoen. Higher SD values in the north than in the south could be expected from the long potential sunshine duration in the Nordic summer (Tikkanen 2005) but are not recorded on an average base.

Differences between potential and actual SD are also due to the effects of topographic situation. A comparison of SD values for Bergen (Bergen-Florida, 67° 20′ N) and Gardermoen at nearly the same latitude along the relatively small W-E distance of 320 km shows differences comparable to those between Tromsø and Kristiansand. In western Norwegian Bergen, frequent precipitation—as discussed above—leads to increased cloudiness. Additionally, the station Bergen-Florida is situated close to the Byfjord at 45 m a.s.l. in a U-shaped glacial valley while there are surrounding mountains up to 673 m a.s.l. at a distance of 5 km, which leads to substantial horizon limitation and, thus, reduced actual sunshine duration (see Sect. 2.6 on Regional and topoclimates).

Solar radiation (SR) input in Norway is less dependent on anthropogenic aerosol as Northern Europe generally has lower particle concentrations with further decreasing concentrations at higher latitudes compared to Central Europe (Asmi et al. 2011). Nevertheless, the relatively low sun position in arctic summer causes long pathways of light through the atmosphere and, thus, considerable extinction even in air with lower aerosol content. Although aerosol contents in Norway are less than in more continental or highly industrialized regions, measurements indicate a general trend of decreasing irradiation; between 1950 and 2003 the annual sum of global radiation at a rural site near the Oslofjord is found to be reduced by 2.5% or 3.1% per decade (Grimenes and Thue-Hansen 2006).

2.3 Temperature

The general position of the Scandinavian Peninsula in relation to the Westerlies leads to very frequent advection of maritime air masses. Additionally, these air masses are strongly influenced by the temperature anomaly caused by the North Atlantic Current (Norseth 1987). 'Much of Norway's coastline lies within the Arctic region, but almost all of it remains free of ice and snow throughout the winter' (Alcamo and Olesen 2012).

This ocean current controls the climate of Norway as the oceanic heat content which is carried by the Gulf Stream, as the North Atlantic Current is also called, and its poleward extension, the Norwegian current. The North Atlantic current is part of the Atlantic Ocean's thermohaline circulation (THC). In this circulation, the heat of warm and saline Atlantic water is removed on its way to the Nordic seas by heat losses to the atmosphere and by freshwater inputs. The major drivers of this circulation pattern are differences in density resulting from salt content and temperature of the water (Blindheim 2004). In contrast to surface ocean currents, which are set in motion by winds, the THC provides an effective mechanism for exchanging substantial amounts of deep water across the equator which is also associated with various coupling mechanisms between sea surface waters and deep waters over both hemispheres (Wefer and Berger 2001). The THC in the Atlantic Ocean encompasses the production of the very dense Antarctic Bottom Water in Antarctic area, the travel across the equator, the formation of the warm and highly saline water of the Gulf Stream, the development of the North Atlantic Deep Water in the Nordic seas, including its southward flow, and the formation and circulation of various surface and intermediate water currents.

The Atlantic Bottom Water is formed in Nordic Seas. The Nordic Seas comprise the Norwegian Sea with the two deep basins, the Norwegian Basin and the Lofoten Basin, the Greenland Sea, and the Iceland Sea (Eldevik and Nilsen 2013). The basins are separated from the North Atlantic by the tectonic Greenland-Scotland Ridge. In the Nordic seas, the water temperature of the North Atlantic Current decreases and the highly saline water sinks down to the bottom. However, the southward travel of the bottom water is delayed by the barrier of Greenland-Scotland Ridge which limits the exchange of deep water as the water has to accumulate at the bottom until its thickness enables a flow over the ridge southwards into the northern Atlantic Ocean (Mauritzen 1996; Loeng and Drinkwater 2007). Estimates of the outflow of the Atlantic Bottom Water range from 15 to 20 Sv (Wefer and Berger 2001; SV = Sverdrup; 1 Sv = 10^6 m^{-3} s^{-1}). The overturning circulation resulting from the inflow of Atlantic water is compensated by fresh polar water at the surface. This water forms the Arctic surface layer above the Atlantic water and the main outflow and freshwater source for the Atlantic Ocean (Dickson et al. 2008; Isachsen et al. 2007). An additional source of surface water is provided by the Norwegian Coastal Current. This current is a continuation of the Baltic Sea outflow through the Skagerrak and carries low-salinity waters along the Norwegian coast to the Barents Sea (Christensen et al. 2018). The Norwegian Coastal Current forms the upper layer of the Norwegian Sea above and alongside the higher saline water of the Atlantic Ocean (Robert and Bousquet 2018).

The influences of the THC on the climatic conditions in Norway are indicated in the warm surface water entering the European Nordic Sea with a temperature of more than 8 °C (Blindheim 1989). With respect to the prevailing westerly winds, Norway lies downwind of the ocean having annual air temperatures nearly everywhere below 8 °C and the heat transferred from the ocean to the air is carried by the westerly winds. Figures on the heat loss of the North Atlantic Current in the Nordic Seas depend largely on the precise calculation of volume flux of the current. Mosby (1974) estimated that about 195.5 TW of the heat of the Nordic Sea are lost by evaporation, whilst 87.8 TW are lost by convection. More recent studies of the heat loss in the Nordic Seas range from 220 to 250 TW (Simonsen and Haugan 1996). In a detailed analysis of the mean volume and heat fluxes of the Atlantic water in the Svinøy section running north-westward from the Norwegian coast at a latitude of 62° N, Skagseth et al. (2008) estimated the volume flux and the heat loss of 4.3 Sv and 126 TW.

The North Atlantic current moderates the annual range of temperatures particularly along the coastal areas of Norway. During the winter months, the air temperature is usually lower than the water temperature of the North Atlantic Current which results in higher evaporation rates in the winter than in spring and summer and moist air masses are carried with the westerly winds. In summer and spring, the air masses are warmer than the ocean water, and there is a reverse effect, when the relatively warm air is advected over the cooler ocean water as the air transfers heat to ocean water and becomes cooler (Tikkanen 2005). The role of the North Atlantic current is indicated in the relatively narrow annual range of temperatures characterized by relatively mild winter temperatures and moderate summer temperatures and in the increase in seasonal differences in temperature from the coastal areas in the west towards the eastern hinterland (Tikkanen 2005). Direct consequences of the warm water of the North Atlantic Current are the ice-free harbours in the winter along the whole Norwegian coast which stand in striking contrast to the harbours in the northern Baltic Sea in the east.

The frequent advection of relatively warm and humid air masses towards the Norwegian mainland and its effects lead to considerable temperature variations (Norseth 1987). Especially the distance from the sea is an important factor, which modifies the general trend of increasing temperature level from north to south, but also location and altitude of mountain ranges have considerable effects. This can be seen from the station data of average temperatures in Fig. 2.3 which pairwise represent extreme places for North, Mid- and Southern Norway each and additionally a station near the southernmost point of Norway.

In the north, Finnmarksvidda (station Kautokeino, 307 m a.s.l.), an inland plateau about 150 km from the open sea, is 5.1 °C colder than Tromsø (100 m a.s.l.) on an island in the Tromsøy Sound about 30 km from open sea (3.8 °C after correction by an average lapse rate of 0.65 °C/100 m). The elevated inland plateau of Dovrefjell in central Norway (station Fokstugu, 973 m a.s.l., about 130 km from open sea) is 5.4 °C colder but 0.8 °C warmer—if altitude-corrected in the same way—than Værnes (12 m a.s.l.; both stations at about 63° N) at the open Trondheimsfjord with its undulating landscape. This indicates that the mountain station is too 'warm' in view of its altitude which can be explained by virtually lower lapse rates in maritime climates due to release of latent heat, which is also reported from other maritime mountain regions (Sattler et al. 2016). There are also seasonal variations; Skre (1971) calculates average

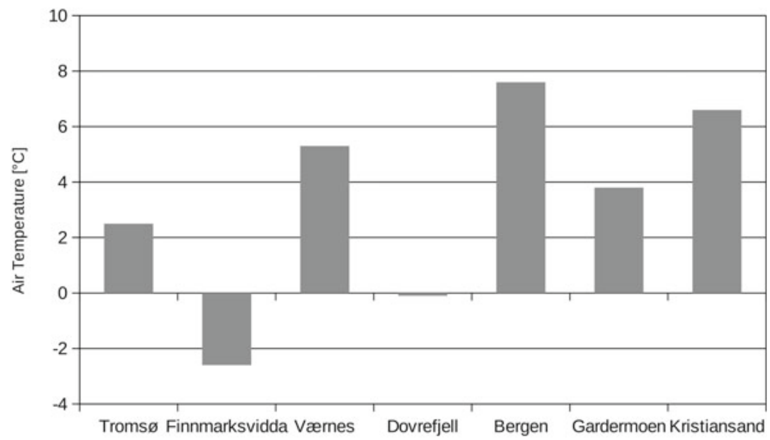


Fig. 2.3 Average annual air temperatures at Norwegian stations 1961–1990 (*Data source* NMI 2018b)

lapse rates between 0.4 °C/100 m (January) and 0.7 °C/100 m (April and July), the latter being the typical average lapse rate as a combination of times with dry and moist lapse rate and the former certainly including days with temperature inversions. The Norwegian west coast, here represented by the station of Bergen-Florida at 12 m a.s.l., which is situated at a fjord not too far from the open North Sea, shows the highest average temperatures and a difference of 3.8 °C (corrected 2.6 °C) to Gardermoen, an inland station at 202 m a.s.l. about 320 km from Bergen (both at about 60° N). This smaller corrected difference—compared to Tromsø-Kautokeino—does not match the larger distance to the coast; here, considerable foehn effects by the Southern Norwegian mountain range are concerned (Tikkanen 2005). Kristiansand with the southernmost weather station with long time series (at 58° N) is colder than Bergen although also situated not far from the sea and further southward. This region is not exposed to the open North Atlantic and continuous westerly winds but it is situated at the Skagerak which is a more continentally influenced marginal sea.

The coldest winter temperature in Norway was recorded in central Finnmark (Karasjok, −51.4 °C; Tikkanen 2005); inland Northern Norway shows extremely low minimum temperatures during nearly all months of the year, but in summer the lowest temperatures occur in the Jotunheimen Mountains in south-western Norway (Fannaråki weather station). The absolute minimum temperatures in the different regions are irregularly distributed with a wide range, which is due to distance to water bodies and more or less intense topoclimate effects of nocturnal cold air drainage. The highest summer extreme temperatures were generally measured in Eastern Norway, the region east of the southern Scandinavian Mountain Range at lower altitudes and greater distance to the northern Atlantic (maximum temperature T_{max} + 35.6 °C, Nesbyen, Buskerud region; Tikkanen 2005). But the range of summer maximum temperatures at low altitude stations in the Norwegian regions is very small, as the lowest maximum temperature is reported from the South Agder region with +32.6 °C and even Finnmark had an extreme heat event with up to 34.3 °C. Relatively high temperatures in the other seasons were reported from stations in various regions, especially where exposed to intense foehn effects normally on the east side of the Scandinavian Mountain Range (Tikkanen 2005), but in fact often also in the opposite direction as can be seen from extreme high winter temperature events at the west coast (18.9 °C on 23.2.1990 in Sunndalsøra; Tikkanen 2005).

At all stations the warmest month is July and the coldest is January (Fig. 2.4). All stations tend to an additional phase lag in their annual cycle with higher temperatures in August compared to June which has been described by Skre (1971), with the exception of the more continental stations Finnmarksvidda and Gardermoen. The annual temperature cycle as given by monthly air temperatures at coastal stations shows maritime effects with small amplitudes (Tikkanen 2005). The differences between coastal and inland stations in northern (Tromsø and Finnmarksvidda) and Southern Norway (Bergen and Gardermoen) are very small and even inverse in summer (−0.6 and −0.9 °C) but marked in winter (11.6 and 8.5 °C). For Værnes and Dovrefjell in central Norway, the differences do not fluctuate strongly throughout the year (5.6 °C in winter and 4.1 °C in summer). Kristiansand is the warmest of these stations in summer; in spring, it is hardly warmer than central-Norwegian Værnes. The negative summer differences between coast and inland are the result of low seawater temperature in the North Atlantic and marked warming of Scandinavian inland areas in summer, whereas shallow or calm fjord water—like the Trondheimsfjord near Værnes—may warm up at least superficially.

The number of freeze–thaw days (Fig. 2.5, left; days with $T_{max} > 0$ °C and $T_{min} < 0$ °C; calculated from NMI 2018b) shows no clear tendency, and the variation is small. Along the coast, Bergen (49d, all values rounded down) has the least number of freeze–thaw days but to the south the number increases (Kristiansand, 85d) as well as to the

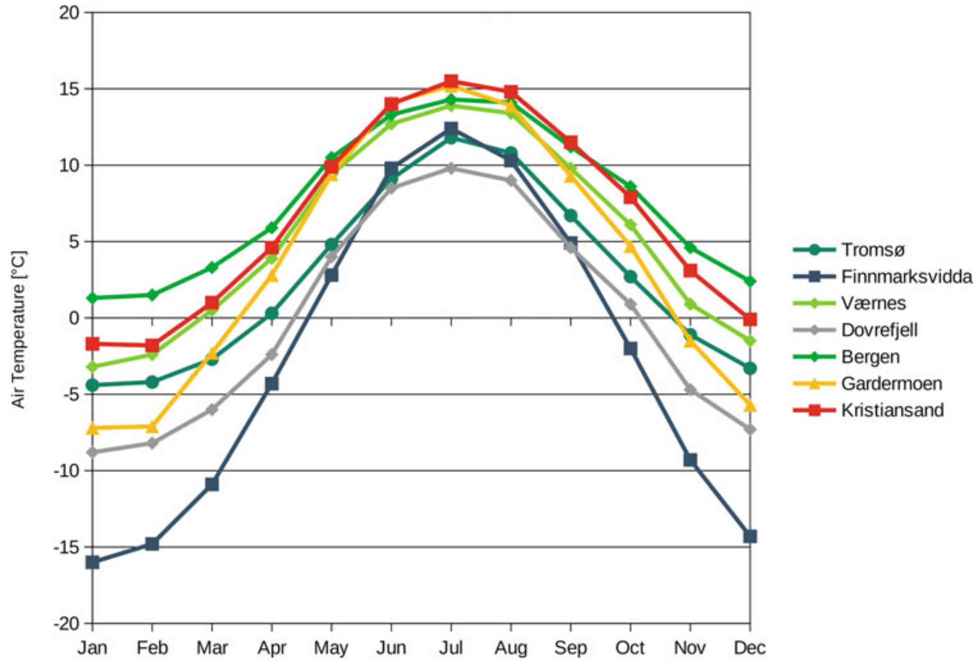
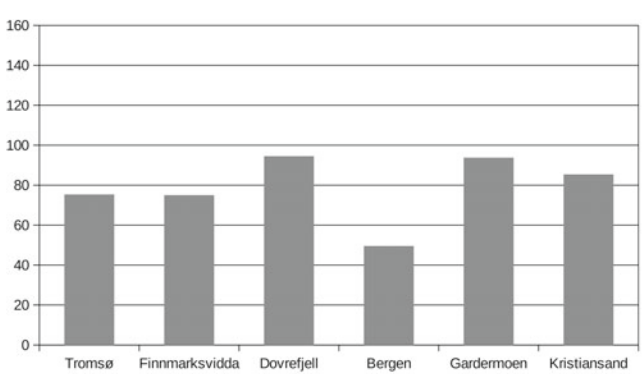


Fig. 2.4 Monthly average air temperatures at Norwegian weather stations 1961–1990 (*Data source* NMI 2018b)

north (Tromsø, 75d). The inland stations are also not systematically different from the coastal counterpart as Finnmarksvidda (75d) does not differ from Tromsø but Gardermoen (93d) does differ from Bergen. There is even no simple systematic difference to expect as the daily temperature cycle results from complex processes (Ketzler 2014) and its range intersects the freezing temperature of water in a complex way during the year.

In contrast to this, the number of ice days at the stations (Fig. 2.5, right; days with $T_{max} < 0$ °C and $T_{min} < 0$ °C; calculated from NMI 2018b) differs considerably and systematically at the stations. Ice days occur rarely along the South Norwegian coast (Bergen: 12d, Kristiansand: 33d, Værnes: 43d) but more frequently at southern inland station Gardermoen (79d). Northern coastal station Tromsø has more ice days (94d) than Bergen but much less than inland station Finnmarksvidda (159d). And—according to the tendencies in annual average temperature—Dovrefjell (133d) does not differ much from Finnmarksvidda but clearly from not very distant Værnes.

The annual cycles of freeze–thaw days for the stations (Fig. 2.6, left; calculated from NMI 2018b) show relatively small differences in amplitudes but a remarkable bimodal distribution and different compression. Finnmarksvidda (<1d) and Dovrefjell (1d) are the only stations with freeze–thaw days in all months; at the same time, they have the least number during winter. The two local maxima are closest to the summer also at these stations, for Bergen, Værnes and Kristiansand, they are closest to the winter months and they also have the greatest number of freeze–thaw days; for the other stations, the characteristics of the annual cycle are in between.



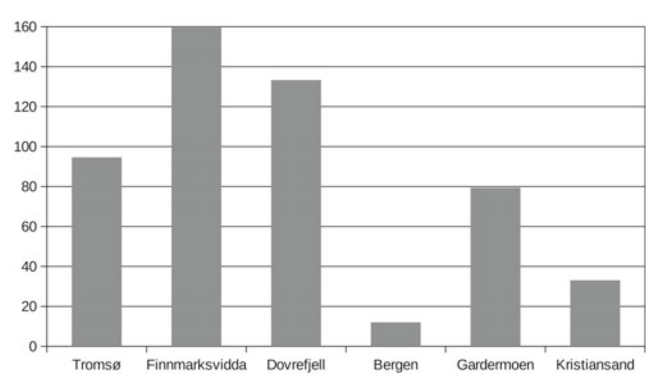


Fig. 2.5 Average annual numbers of freeze–thaw days (left) and ice days (right) at Norwegian weather stations 1961–1990 (calculated from NMI 2018b)

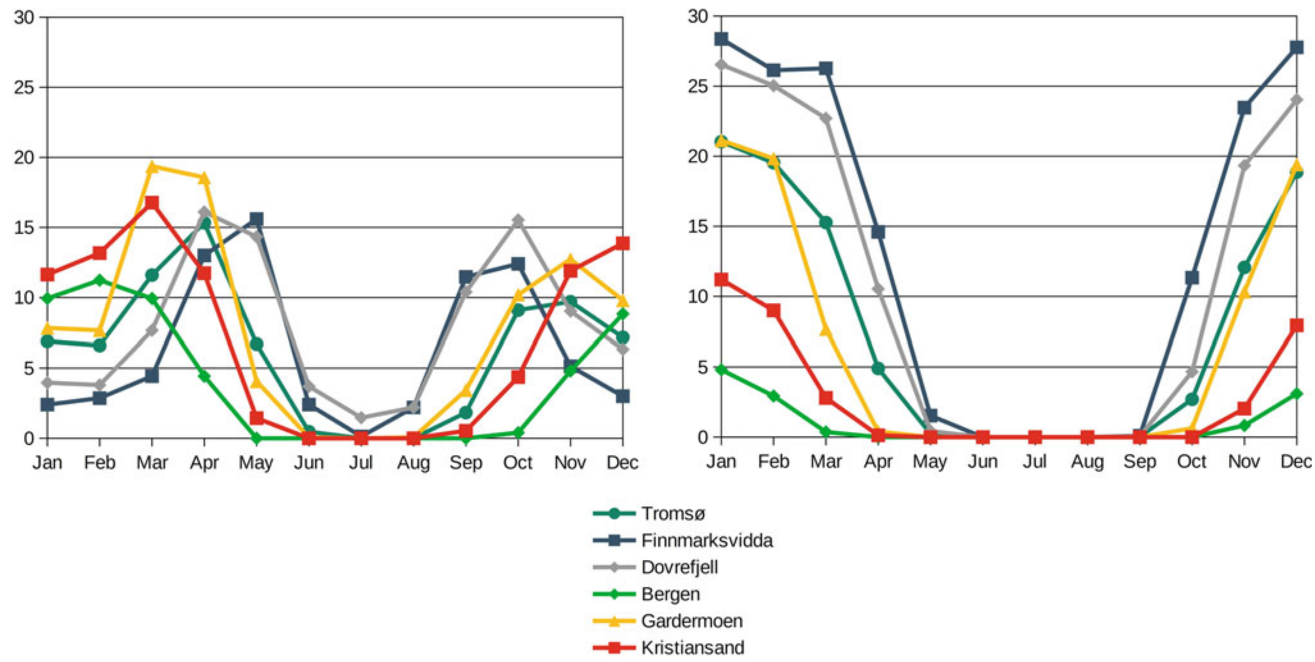


Fig. 2.6 Annual cycle of the monthly number of freeze–thaw days (left) and of ice days (right) at Norwegian weather stations 1961–1990 (*Data source* NMI 2018b)

The bimodal distribution of the freeze–thaw days is caused by the superimposed distribution of the ice days with its maximum in winter (Fig. 2.6, right; calculated from NMI 2018b). Besides the fact, that ice days do not occur in climatological summer at any of these stations, their annual distribution generally resembles the annual average. But it is to mention that the number of ice days in South Norwegian Gardermoen in January (19d) equals the number in North Norwegian Tromsø.

On the basis of climate data from geostatistical modelling by NMI (Lussana 2018) the average air temperature distribution in Norway and its variation can be calculated. In Fig. 2.7, the average air temperature (left) and the average absolute year-to-year temperature deviation for the period 1961–1990 are given on the base of these 1 km resolution data.

The above-mentioned trend of increasing temperature from north to south and the overlying effect of decreasing temperature with distance from the sea can be recognized in Fig. 2.7 (left) by a widening belt of moderate and increasing temperatures along the coast. The level of 6–7 °C can be approximately identified with the timberline in the boreal zone (according to Körner and Paulsen 2004). While the Southern Norwegian mountain range forms a marked area of low average temperature due to its elevation up to 2469 m a.s.l. in Jotunheimen (Galdhøppigen) and 2209 m a.s.l. in Dovrefjell (Snøhetta), the large North Norwegian area of a similar low-temperature level is situated in the low mountain area of Finnmarksvidda of only up to 600 m a.s.l. The undulating landscape around Central-Norwegian Trondheimsfjord and its hinterland along Stjørdalen (near Værnes) towards the, here, low-lying Scandinavian watershed situated far inland forms a region with a generally very moderate temperature level (see Fig. 2.8).

The average absolute year-to-year temperature deviation (Fig. 2.7, right) forms three different patterns: a more diffuse areal structure in the South-Eastern, Central- and North Norwegian inland, a more distinct microstructure mapping valleys and separated mountains, both showing a low absolute average temperature deviation, and also a more diffuse structure in some coast regions with small deviations. The former apparently represents regions of frequent high continental (probably in summer), the latter of constant maritime influence on the temperature regime. The areas of high deviation in microstructure indicate a role of special topoclimate effects.

Proxy data show a general cooling tendency over several centuries with the coldest period in the eighteenth century ('Little Ice Age'). From temperature estimates, average summer temperatures were estimated for that time to be about 1 °C lower than in the period 1971–2000. From the beginning of twentieth century, when instrumental observation data exist from the main regions of Norway, the overall average temperature remained about 0.5 °C below the level of 1971–2000 with a temporarily higher level in the 1930s. Since 1990, the 1971–2000 level is exceeded nearly constantly (Hanssen-Bauer et al. 2017). On the basis of data for those stations used in this paragraph which exist—with

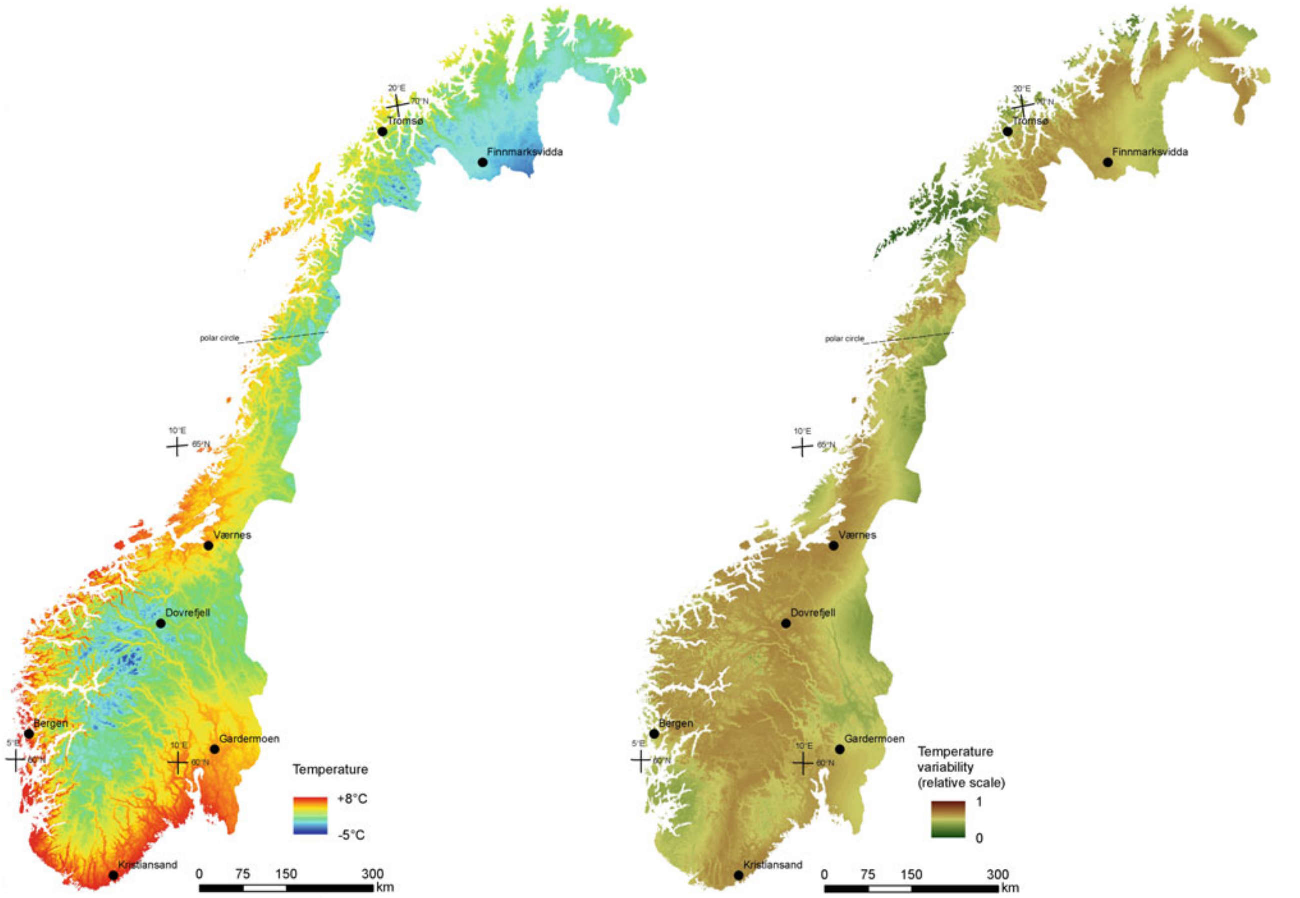


Fig. 2.7 Average air temperature (left) and the average absolute year-to-year temperature deviation (right) for the period 1961–1990 (*Data source* Lussana 2018)

partly minor changes of station location—for the last nearly 100 years, linear trends from regression analysis were computed: Kristiansand, Bergen, Dovrefjell (Fokstugu/Fokstua), Tromsø and Finnmarksvidda (data from NMI 2018b; a homogenisation for the whole period and all stations, as applied for parts and some stations in Lundstad and Tveito 2016, was not available).

As shown in Table 2.1, all of the time series have a positive trend on an annual base (average: 1.0 °C/100a) with the inland and more elevated places Dovrefjell and Finnmarksvidda both having the highest temperature increase of 1.6 °C/100a. All seasons have an average trend which is positive and in all seasons—except winter—all single stations also, with spring showing the strongest trend (1.5 °C/100a) and the weakest trend in summer (0.5 °C/100a). Moberg et al. (2005) cite a general trend for Fennoscandia since late nineteenth century of 0.6 °C. Winter is the only season with marked contrary trends: while there is a negative or weak positive trend at places at the coast, the inland and elevated places Dovrefjell and Finnmarksvidda have experienced a distinct warming. Here, the winter temperatures have increased with more than 1.2 °C since the middle of the last normal period 1961–1990.

A warming trend of less than 1.0 °C/100a (annual mean temperature) at coastal stations which is below the global average may be caused by the special sensible to latent energy flux relation over the oceans (Byrne and O'Gorman 2018) and may lead to a delay of global warming effects in these regions. However, the inland areas like Dovrefjell and Finnmarksvidda show a marked temperature increase, which is observed especially for the lasts decades in inland Scandinavia (Alcamo and Olesen 2012). This trend has severe consequences as these stations are situated in potential permafrost areas with an annual temperature level of 0 °C or below (marked by the blue colours in Fig. 2.7, left). An above-average warming (Table 2.1) and an increased frequency of extreme summer heat events (see Fig. 2.9) are expected to accelerate permafrost thaw with—inter alia—the effect of increased slope instability (e.g. Blikra and Christiansen 2014; Harbitz et al. 2014). In the period 1981–2010 in about 6% of mainland Norway's land area permafrost existed and, as arose from intermediate

Fig. 2.8 Summer aspect of central-Norwegian landscape towards the Skarvan and Roltdalen National Park (*Photo* Gunnar Ketzler, 26/7/2018)

Table 2.1 Linear temperature trends for places in Norway for the period 1921–2018 (in °C per year; green: <0 °C/100a, yellow: <1 °C/100a, orange: <2°/100a, red: ≥2°C/100a

	Spring	Summer	Autumn	Winter	Year
Kristiansand	0.016	0.01	0.004	-0.006	0.004
Bergen	0.009	0.008	0.011	0.008	0.009
Dovrefjell	0.017	0.002	0.013	0.029	0.016
Tromsö	0.016	0.001	0.007	-0.001	0.006
Finnmarksvid	0.017	0.004	0.013	0.029	0.016
Average	15	3.75	9.6	11.8	10.2

investigations, it already partly thawed and disappeared in the years after (Hanssen-Bauer et al. 2017).

2.4 Precipitation

If there is a clear general precipitation gradient in Norway, then it is directed from the coast to the inland areas (Fig. 2.10). In the North, the recordings show two and a half times as much annual precipitation 1961–1990 in maritime Tromsø (1031 mm) than in inland Finnmarksvidda (Kautokeino: 376 mm). In central and West Norway, the relation is similar: Værnes has twice as much precipitation (892 mm) as Dovrefjell (Fokstugu: 435 mm) and Bergen (2250 mm) two and a half times as much as the inland station Gardermoen (862 mm). And even in the coastal place Kristiansand, the southernmost station used in this study, the amount of precipitation is considerable (1299 mm) although, here, the westerlies are of less importance and only more southerly winds can contribute to this effect. These data also point to a certain gradient from north to south which is to be expected as a result of an increasing temperature level, but the complex relief situation is apparently of greater and clearer effect on precipitation.

The monthly distribution (Fig. 2.11) shows two distinct precipitation regimes: while the annual courses of precipitation at Finnmarksvidda and Dovrefjell have a marked maximum in summer (July) with a fast decrease in autumn, the precipitation maximum at the other stations is recorded in September or October (November). The latter can be

Fig. 2.9 Patterned grounds on Finnmarksvidda, Finnmark, 69.6° N, as a result of arctic climate conditions (Köppen type ET). The sky above with typical 'fair-weather clouds' of temperate environments (cumulus humilis, cu hu), indicating relatively high temperatures (the clouds completely consist of water droplets) and a marked positive energy balance at ground level recognizable by intense convection (summer heat period in 2018, *Photo* Gunnar Ketzler, 31/7/2018). An increased frequency of such summer heat events is expected to accelerate permafrost thawing and related geomorphological processes

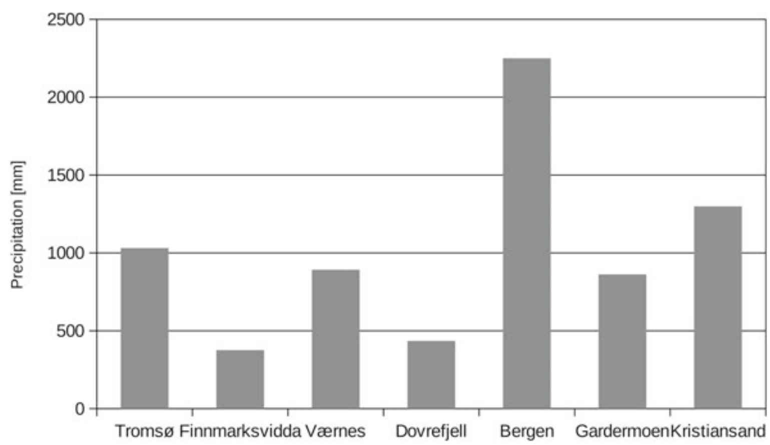


Fig. 2.10 Mean annual precipitation [mm] for Norwegian stations, precipitation normals 1961–1990 (*Data source* NMI 2018b)

associated with increased activity of the polar front system in autumn; a positive NAO phase is generally expected to correspond with higher precipitation normals in Scandinavia, especially along the western mountain slopes (Wibig 1999; Quante et al. 2016). The former is a typical inland regime with effects of convective precipitation events (Norseth 1987), which can be seen in inland mountain areas as well. All series have their minimum in April or May with Gardermoen and Værnes showing the smallest precipitation amounts. This is the inverse effect of the strong polar front system in autumn leading to a weaker activity of the westerlies in Norway in spring and more frequent stable anticyclones over Scandinavia as a ridge of an anticyclone in Russia (Johanessen 1970). The consequence is a dry and sunny weather type with southern or south-easterly winds in Norway including foehn effects on the west side of the Scandes.

The geographical distribution of precipitation in detail is given by results of geostatistical modelling using station data for the period 1961–1990 (Crespi et al. 2018; Fig. 2.12, left). Large areas along the South Norwegian west coast and along southern parts of the North Norwegian coast show remarkable amounts of annual precipitation (>3000 mm; dark blue). In some regions, the model data indicate results of >4000 mm—also in the northern Svartisen–Saltfjell region —and in a small area north of Bergen with the Ålfotbre Glacier even >5000mm (west of Jostedalsbre Glacier, the greatest plateau glacier in continental Europe and the

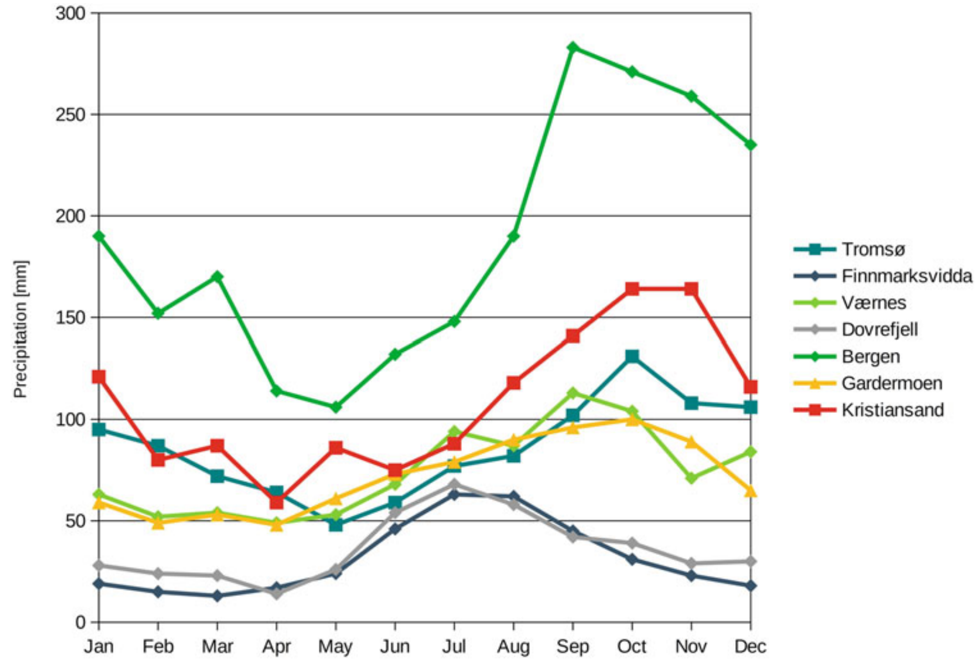


Fig. 2.11 Mean monthly precipitation [mm] for Norwegian weather stations, precipitation normals 1961–1990 (*Data source* NMI 2018b)

Jotunheimen Mountains with the highest summits of Scandinavia). Almost all coastal regions are marked as having moderate (>1000 mm; green) or considerable annual precipitation (>2000 mm; light blue). Only in the Oslofjord region the coastal areas have less than 1000 mm. It is obvious that the areas with largest precipitation amount are especially the western slopes of the Scandinavian Mountains as a result of air mass advection (Norseth 1987; Wibig 1999). But in detail, these are not the high mountain areas themselves but distinctly the zone in front of (relative to the prevailing westerly winds) like Brekke at the outer Sognefjord near the coast with 5596 mm of annual precipitation in 1990 (Tikkanen 2005) or more inland at an altitude rather typical for low mountain areas like the Ålfotbre Glacier at an elevation of <1400 m a.s.l. with estimated 5000 mm as annual average (Tikkanen 2005).

The locations of extreme daily precipitation events are concentrated in three areas at the windward coastal foreland of the Scandes, the distribution of which not showing exactly the same pattern as the annual extremes: the Norwegian south-west near Stavanger, the west side of the Jostedalsbre Glacier/Jotunheimen Mountains and the west side of the Saltfjell Mountains with the Svartisen Glacier. In Fig. 2.12 (left), the 10 most intensive events 1950–2008 are marked (Lupikasza 2016).

The inland regions are widespread characterized by relatively small amounts of precipitation (<600 mm; yellow). In Finnmark, greater areas have less than 500 mm. In some areas around Dovrefjell, an average annual precipitation of even 300 mm is not exceeded. Here, summers may be dry and agriculture, for which the greater valleys on the leeward side of the Jotunheimen Mountains with a foehn situation are very favourable due to relatively high temperatures and long sunshine duration is depending on irrigation.

The intra-annual variability of precipitation calculated as average absolute deviation of all monthly values relative to the average monthly precipitation on the basis of the average annual precipitation 1961–1990 shows a partly different pattern (calculated from NMI 2018b; Fig. 2.12; right). Relatively high values of variability (blue) show both mountain and inland areas. Along the watershed of the Scandinavian Mountains, this can be interpreted as an effect of a seasonal variable transport range of humid maritime air masses. In the more continental inland regions like the eastern part of Southern Norway or Finnmarksvidda, variability is expected to be connected to more or less intense high-pressure phases, which disconnect these areas completely from westerly winds (Johanessen 1970; Wibig 1999). Between these zones of great variability, a belt of small variability crosses great parts of the country from north to south including the Oslofjord and Trondheimsfjord region indicating a relatively even distribution of precipitation throughout the year.

The return periods (RI) for intense precipitation events (10 mm/d) in all months of the year cluster in two groups without any other apparent regional tendency as described in connection with the annual course (Fig. 2.13). Finnmarksvidda and Dovrefjell show an RI value of considerably more than 100 days, all other stations of about 10 days. For the former, this means an occurrence of these events of about twice a year, for the latter about once in a week or every second week. There is no massive difference between the data for the whole year and the months of March to

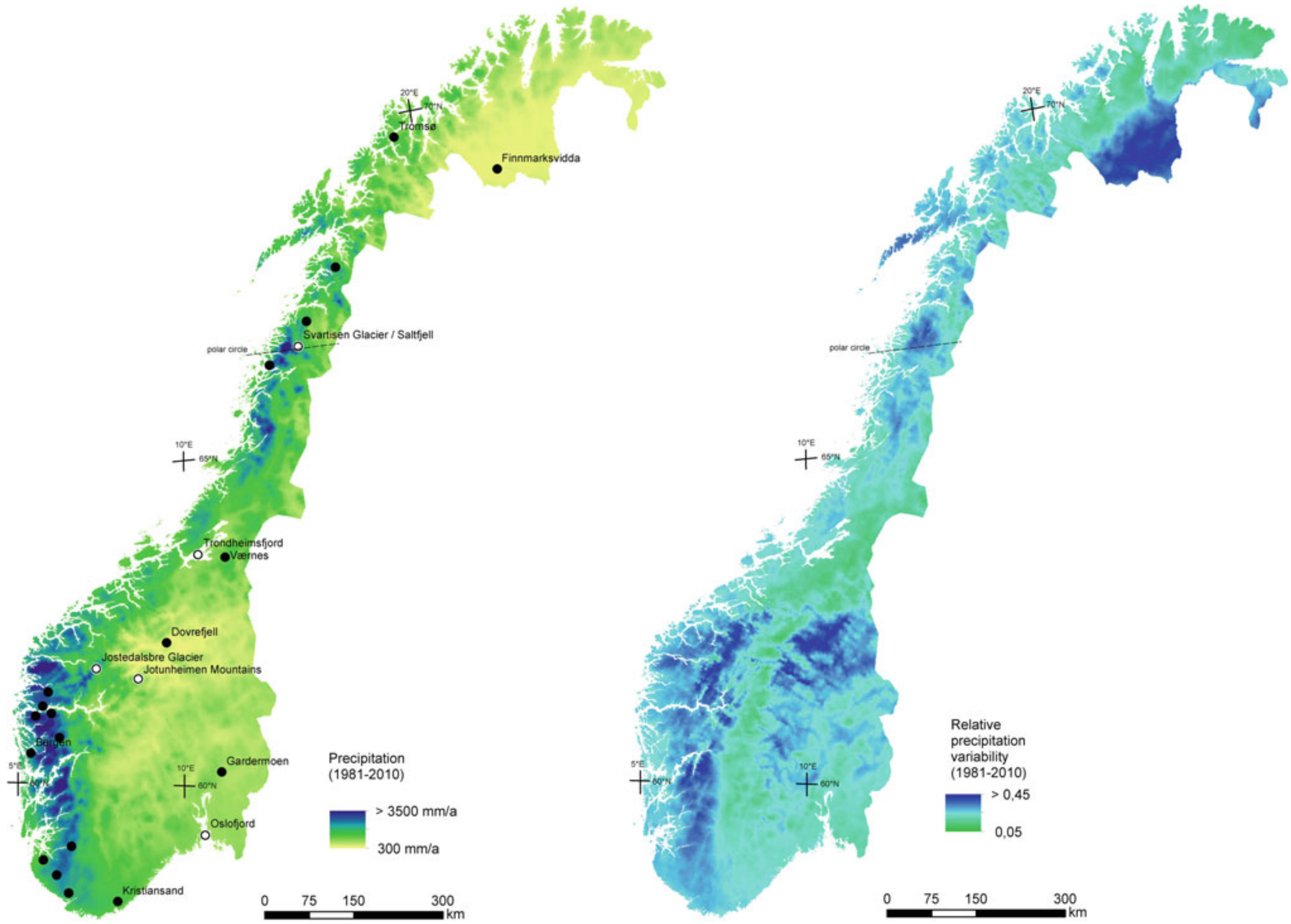


Fig. 2.12 Precipitation in Norway on the basis of station data and geostatistical modelling for the period 1961–1990 (*Data source* Crespi et al. 2018; Lussana and Crespi 2018)—average annual precipitation (left) and average relative month-to-month precipitation deviation calculated on the basis of monthly averages (right). Dots in Fig. 2.12 (left): locations of extreme daily rainfall events (after Lupikasza 2016)

Fig. 2.13 Return periods (RI) of 10 mm daily rainfall for Norwegian weather stations calculated from daily precipitation data 1961–1990 (calculated from NMI 2018b) for the whole year and the months March to November