Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Natural Sciences
Department of Geography

Levente Samu

Impacts of climate change on glacier runoff and hydropower production in Norway

Master's thesis in Natural Resources Management, Geography
Supervisor: Irina Rogozhina
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Abstract

Human-made climate change poses a significant threat to freshwater resources worldwide. Despite the fact that mountain glaciers contain only a minor share of the planet's freshwater, glacier melt provides invaluable contributions to the summer river discharge in many mountainous regions, such as Central Asia, South America and Europe. Since the cryosphere is among the most sensitive and rapidly responding components of the Earth's surface under warming climate conditions, there is a substantial motivation for assessing potential impacts of change in glacier runoff regimes on societies in regions with high glacier cover.

This study sheds light on the past and future changes in runoff regimes of four highly glacierized catchments in Norway, zooming in on possible impacts of such changes on hydropower production. It builds upon an interdisciplinary approach that merges the physical and social branches of geography. Historical reconstructions and future projections of glacier runoff are based on a fusion of observational data, climate models and surface mass balance simulations, whereas semi-structured open-ended interviews with hydropower experts aim at estimating probable impacts of predicted changes in runoff regimes on the hydropower industry.

The four glacier systems addressed in this study exhibited stable mass-balance and length characteristics between the 1960s and 1990, followed by a period of general advance and mass gain in the early1990s. However, negative annual balances and significant retreat have dominated every studied glacier catchment since 2000. In the four study basins central to this thesis total runoff has increased in the recent past, albeit with a more significant rise and larger variations within marine-proximate catchments. The reconstructed general increase in the total runoff is in part due to an enhanced contribution of glacier melt and in part due to higher precipitation. In particular, a more substantial contribution of glacier meltwater to total runoff is found in basins with substantial climate continentality, where runoff regimes are strongly influenced by variations in temperature and much less so by changes in precipitation.

Future projections under two greenhouse gas concentration scenarios suggest that runoff will remain relatively stable for the representative concentration pathway (RCP) 4.5 and will show moderate increases for RCP 8.5 at the four study sites during the 21st century. The relative contributions of both glacier melt and snowmelt to the total runoff are estimated to drop, as opposed to a significantly increased share of rain in every catchment, which aligns well with the projected temperature changes during the corresponding period suggesting a strong correlation between the two. Future projections and interviews with hydropower experts indicate that glaciers will likely have a moderate impact on hydropower production in Norway in the 21st century. However, a more frequent occurrence of unusually dry periods during the summer periods may elevate the importance of glacier meltwater for hydropower production in the future.

Sammendrag

Klimaendringer forårsaket av menneskelig aktivitet utgjør en stor trussel mot ferskvannsressurser over hele verden. Til tross for at bare en brøkdel av Jordas ferskvann er lagret i isbreer, bidrar bresmelte betraktelig til sommervannføringen i fjellområder i blant annet Sentral-Asia, Sør-Amerika og Europa. Kryosfæren er blant de mest følsomme deler av Jordas overflate og den kan raskt forandre seg i takt med global oppvarming. Det er derfor et stort behov for å vurdere mulige konsekvenser av endringer i avrenning av smeltevann fra isbreer i bebodde områder.

Denne studien tar for seg fire nedslagsfelt i Norge som er i stor grad dekket av isbreer og belyser endringene i avrenning av smeltevann. Det blir også gjort en nærmere undersøkelse på mulige konsekvenser av slike endringer på vannkraftproduksjonen. Studien tar i bruk fysisk geografisk data i form av observasjoner, klimamodeller og simulasjoner av massebalanse for å rekonstruere fortidens avrenningsmønstre samt forutsi hvordan mønsteret blir i fremtiden. I tillegg blir det brukt samfunnsgeografisk data i form av semistrukturerte intervju med vannkrafteksperter for å anslå effekten av endringer i avrenning på vannkraftindustrien.

De fire isbreene hadde stabil massebalanse og lengde i perioden 1960-1990, mens det tidlig på 90-tallet skjedde økning i utbredelse og masse. Denne vekstperioden var etterfulgt av negativ balanse og betydelig tilbakegang på alle fire nedslagsfelt, men netto avregning har økt i det siste. Denne økningen skyldes et større bidrag fra bresmelte, i tillegg til økt nedbør. Bresmelte bidro i størst grad i basseng med betydelig "climate continentality" hvor avrenningsmønstre er sterkt påvirket av temperaturendringer men ikke av nedbør.

Beregninger for fremtiden i to ulike scenarioer tyder på at avrenning vil forbli relativt stabil i "representative concentration pathway" (RCP) 4.5, mens det i RCP 8.5 vil øke ved de fire områdene i det 21. århundret. Det relative bidraget fra både bresmelte og snøsmelte til den totale avrenningen er estimert å avta, mens bidraget fra nedbør forventes å øke. Disse estimatene stemmer overens med de beregnet temperaturendringene for den samme tidsperioden. Beregninger for fremtiden og opplysninger fra intervjuene tyder på at isbreer kommer til å ha en moderat effekt på vannkraftproduksjon i Norge i det 21. århundret. En økt forekomst av perioder med tørke i sommertid kan allikevel føre til en enda større rolle av bresmelte i vannkraftproduksjon i fremtiden.

Acknowledgments

This thesis is the final step of a wonderful journey at NTNU, in the MSc in Natural Resource Management program. I have enjoyed every second of the NARM program, which was made even more memorable by the fabulous people of the NARM family, who provided me with an encouraging and supportive social environment. I feel immensely fortunate for the experiences during the last two years.

When I chose this specific topic to work on, I knew it would not be easy. Saying that my previous education covered glaciology lightly would be an overstatement. Therefore, this study has been an immense learning process. However, the completion of this thesis would not have been possible without numerous people's constant guidance and support.

First and foremost, I would like to express my greatest appreciation for the help and guidance provided by my academic supervisor, Dr. Irina Rogozhina. She supported me along the whole intricate process, and without her insights and supervision, this study would not have been possible. I am also grateful for the honest and direct manner she helped me to improve, and to achieve the objectives set for this thesis, while also developing a good relationship and being able to blend in more casual subjects into our discussions.

I would also like to personally thank Liss Marie Andreassen for being incredibly supportive and guiding me in identifying essential data and selecting study sites. Her contribution was an absolutely vital element of this thesis, which I will remain grateful for forever. Moreover, I can not emphasize my appreciation enough for the help and advice received from Markus Engelhardt, whose guidance in validating and presenting modeled runoff was a massive contribution, and I am very thankful for his support. Furthermore, I would like to say special thanks to my fellow master student, Danielle Hallé, who developed the PDD model and assisted me in interpreting the model and the downscaling procedure. I am incredibly grateful for her efforts to help and encourage me.

Additionally, I can not overlook the contribution of the participants in the interviews: Even Loe, whom we met during fieldwork and provided the project with vital information that facilitated the formulation of the study; Gaute Lappegard, who always provided me with detailed and thorough information whenever I turned to him for advice; and Sigrid Bojesen Fatnes who have answered my questions in great detail and by this, contributed massively to this thesis. I am extremely thankful for their participation and input.

Last but not least, I would like to extend a huge note of thanks to my partner, Anna Parczen, who have always supported me, even on my grumpiest days; and my family, my mother Zsuzsanna, my father Lajos, and my brothers Attila and Kristóf, who had provided me with vital moral support and were always available when I needed encouragement. It would have been a different story without their backing.

Tusen takk!

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List of Acronyms

AO – Atlantic Oscillation

ArcGIS - Arc Geographic Information System

CDFT - Cumulative Distribution Function Transform

CORDEX - Coordinated Regional Climate Downscaling Experiment

CV – Coefficient of variation

DBS - Distribution-Based Scaling

DEM – Digitial Elevation Model

DTM – Digital Terrain Model

ECMWF - European Centre for Medium-Range Weather Forecasts

ELA – Equilibrium Line Altitude

ERA - ECMWF Reanalysis 5th Generation

GCM – General Circulation Model

GHG – Green-House Gas

GOTHECA - Glacier impacts On the Hydrological systems in Europe and Central-Asia

IPCC - Intergovernmental Panel on Climate Change

m.a.s.l. – Meters Above Sea-Level

m.w.e. – Meters Water Equivalent

MATLAB - MATrix LABoratory

NAO – North-Atlantic Oscillation

NetCDF - Network Common Data Form

NS – Nash-Sutcliffe coefficient

NVE – Norges Vassdrag og Energi Direktorat

PDD – Positive Degree-Day

RCA4 - Rossby Centre regional Atmospheric model

RCM – Regional Climate Model

RCP – Representative Concentration Pathway

RMSE – Root Mean Square Error

SLR – Slope Lapse Rate

WS – Weather Station

1. Introduction

Life, as we know it, would not exist without the presence of water on Earth. Fresh-water, in particular, is fundamental for existence of almost any type of life on our planet. Water accounts for 75% of Earth's surface. However, oceans comprise 96% of all water resources on the planet (Shiklomanov, 1993) with a high salinity ratio, making them unsuitable for human consumption. Moreover, freshwater resources are not only scarce but fragile to the effects of climate change as well. The majority (69%) of freshwater resources on Earth is stored in the cryosphere. The cryosphere refers to the Earth elements mainly built up of frozen water, including ice sheets, ice caps, and glaciers. Naturally, the two most prominent ice masses, the Antarctic Ice Sheet and the Greenland Ice Sheet, contain the majority of the freshwater stored in the cryosphere. A report from the United States Geological Survey revealed that the 550.000 km^2 of glaciers and mountain icecaps found on Earth account only for 4% of all the freshwater resources locked in the cryosphere (United Nations Environment Programme, 2002).

Glaciers may not be the most substantial freshwater resources, but they are crucial sources of water in some highly populated parts of the planet, such as arid, continental parts of Central-Asia, where a considerable share of summer runoff is derived from glacier meltwater (Armstrong et al., 2019). Glaciers act as natural water reservoirs by accumulating winter precipitation and releasing it during the melting season (Huss et al., 2010). Climate change, however, poses significant challenges to glacierized basins considering that the majority of glaciers have been shrinking since the early 20th century on a global scale (Vaughan et al., 2013), causing changes in the volume, seasonal distribution and timing of runoff.

Most of Earth's glaciers have been rapidly shrinking (Vaughan et al., 2013) since the end of the Little Ice Age and the beginning of massive global industrialization. Glaciers and ice caps are sensitive climate indicators. While swiftly retreating glaciers may result in increased meltwater discharge in the near future, this tendency will likely reverse, impacting most heavily regions with limited precipitation and the impacts may be most decisive during the ablation period, when discharge in catchments with a high glacier cover often rely on glacier melt to an extensive degree. The decreasing contribution of glacier melt may also cause severe complications and water shortages in drought-prone, arid regions of the world. Moreover, as glaciers are shrinking, the timing of annual peak runoff of rivers partly relying on glacier melt is also shifting. Peak flow varies widely geographically, and alterations in its timing may cause extreme and unpredictable floods, which pose massive threats for the population down-stream (Beniston et al., 2018). The European mountain cryosphere is no exception, as it is heavily affected by climate change. Glaciers in Europe were one of the first hit by climate change and have been impacted ever since (Vaughan et al., 2013).

Norway has the largest share of ice-covered land in mainland Europe (Beniston et al., 2018), and except for a short period of glacier advance in the 1990s (Nesje et al., 2000, Vaughan et al., 2013), rapidly retreating glaciers have been observed in Norway as well. Glacier monitoring dates back to the 1900s, when measurements of glacier frontal positions started. Since then, glaciers in Norway have retreated by a total of 2,5 km (Hanssen-Bauer et al., 2017), and glacier extent have decreased by 11%, with considerable variations among individual glaciers (Winsvold et al., 2014). Experts anticipate this tendency to continue in the foreseeable future with glaciers shrinking to 1/3 of their current area and volume, whereas smaller mountain glaciers face probable complete recession or withdrawal to higher altitudes (Hanssen-Bauer et al., 2017). Other studies have predicted an even more drastic retreat and disappearance of glaciers across Scandinavia, with south-west Norwegian glaciers projected to shrink by 80-100% (Bosson et al., 2019).

At the same time, annual mean temperatures have increased significantly in Norway since the second half of the 20th century, and intensifying climate change will likely lead to increasing in temperature, precipitation, changing ocean currents, and alterations in atmospheric circulations (Hanssen-Bauer et al., 2017) in the future. An average temperature rise of 4.5 ºC is projected in Norway, with an uncertainty range of 3.3 ºC to 6.4 ºC. At the same time, climate experts expect precipitation to increase by a magnitude of 18% (7% - 23%) according to the report: Climate in Norway 2100 (Hanssen-Bauer et al., 2017). Increasing temperatures and precipitation have resulted in generally higher annual runoff rates. As reported by Engelhardt et al. (2014), runoff in glacierized catchments exhibited a general increase and an average growth of 5% – 20% in the contribution glacier meltwater to the total runoff between 1990 and 2010 in three strongly glacierized basins in Southern and Western Norway (Engelhardt et al., 2014).

The topographic settings of Norway coupled with high runoff rates provide a strong basis for hydropower development in the country, which is well demonstrated by the fact that, according to previous studies, Norway carries the largest hydropower potential in Europe (Farinotti et al., 2019). Hydropower is, however, already a vital element of the Norwegian energy sector since 96% of the energy produced annually is generated by hydropower (Graabak et al., 2017).

This study is a part of the bigger-scale GOTHECA (Glacier impacts On The Hydrological systems in Europe and Central Asia) project based on the collaboration of the Department of

Geography at NTNU with various institutions in Norway, such as the Norwegian Energy and Water Directorate. GOTHECA is a multidisciplinary effort aiming at comprehending the effects of climate change on glaciers and hydrological systems by integrating various climate datasets and glacier runoff modeling in the European Alps, Scandinavia, and High Asia. As a part of the GOTHECA project, this study aims to shed light on the potential consequences of retreating glaciers on the hydropower industry in Norway by revealing past variations in runoff regimes in four highly glacierized basins, and assembling a future runoff scenario until the end of the 21st century.

1.1. Motivation for Research

Experts predict glaciers to shrink both in area and volume under a steadily warming climate throughout the 21st century (Hanssen-Bauer et al., 2017). Glaciers with more considerable climate continentality are more exposed to climate change and demonstrated a more definite decrease in area and volume. Consequently, intensifying the melting of glaciers may introduce firmly altered discharge regimes in terms of timing and volume of peak flows (Engelhardt et al., 2014), which requires constant monitoring to adjust water management practices and hydropower production accordingly. Despite the total annual precipitation is projected to increase, dry summer periods are occurring more frequently in Norway. During such arid periods, glacier melt discharge is the primary runoff source; hence, the significant retreat or complete disappearance of glaciers may cause substantial complications. Therefore, the comprehensive understanding of temporal and spatial variations in runoff and major drivers of changes in highly glacierized catchments is crucial for adequate adaptation to future changes.

Earlier studies inspired the following hypotheses: glacier contribution to runoff and total runoff will increase steadily or remain stable through most of the 21st century, providing a dependable basis for high discharge rates in glacierized catchments in Norway. Therefore, direct consequences of rapidly retreating glaciers will have a moderate effect on the hydropower industry resulting in minimal socio-economic impacts. Intensifying summer droughts, however, may augment the importance of glacier meltwater in during the summer season.

1.2. Research Objectives

After considering the scope of the study and taking my research interests into account, I formulated the following objectives/ research questions:

- How did glaciers change in the recent past in Norway, and what are the possible climatic drivers?
- How well do different climate datasets perform in the complex topographical environment of Norway and to which extent can downscaling improve their performance?
- How did the contribution of glacier meltwater vary in the last 40 years? What might be the potential causes behind the fluctuations in glacier meltwater discharge, and how these causes differ from region to region?
- Will changes in glacier discharge have a significant impact on the Norwegian hydropower industry in the future?
- To which extent can we trust regional climate model projections to simulate future runoff?

Evaluating glacier melt contribution to the total runoff in highly glacierized catchments is crucial to determine the future effects of retreating glaciers on hydrology. Consequently, understanding the direct impact of glaciers on runoff regimes in such basins will lead to better estimations of possible impacts on local people and regional hydropower development. First and foremost, historical fluctuations of runoff, glaciers, and climate are needed to be analyzed. Another crucial component of the study is to assemble future runoff projections and potentially provide schematic guidance for local water management to detect the significance of meltwater from glaciers regionally. However, the usage of different climate data products may substantially influence the results of simulating both historical and future discharge in glacier dominated basins. Therefore, the evaluation of the global climate reanalysis ERA5-Land and a selected GCM-RCM is involved in this study in order to assess the usability of such climate datasets in hydrology modeling.

Finally, a vital aim of the study and the GOTHECA project is to estimate the impacts of the altered water supply on hydropower, and consequently, on the local population. In Norway, the emphasis is on hydropower production as adapting to the conceivably decreasing glacier discharge may require significant adjustments in this particular industry. In order to shed light on the future effects of glaciers on hydropower production in Norway, quantitative and qualitative research was completed, involving runoff modeling and open-ended interviews with hydropower experts from the leading national energy firm, Statkraft.

Figure 1 - On fieldwork in the Jostedalsbreen region.

1.3. Study Areas

Within the GOTHECA project framework, this study focuses on the impacts of climate-change-induced glacier retreat on hydrological systems and its effects on local communities in Norway. Norway was selected as a study case partly on account of the Scandinavian country's large (2692 km^2) glacier coverage (Beniston et al., 2018); thus, possibly strongly affected by climate change. As previously discussed, one of the main objectives of this study is to estimate the effects of changing glacier melt, and hydrological regimes pose to hydropower production in Norway. Therefore, this aspect was taken into account when selecting study sites.

After consideration, the main criteria for selecting study sites were:

- adequate hydrological data from gauging stations or
- adequate mass-balance records

- potential direct impact on hydropower production
- study areas spreading over the whole country from south to north in order to detect larger-scale trends

Firmly acting according to the criteria above, the following glacier and corresponding catchments were selected: Austdalsbreen, Bondhusbrea, Engabreen, and Rembesdalskåka (see Figure 2).

Table 1 - Overview of the four selected study catchments.

	Engabreen	Austdalsbreen	Rembesdalskåka	Bondhusbrea
Catchment size (km^2)	53	60,7	80,8	60,8
Glacier cover (%)	70	28	42	40
Mean elevation (m.a.s.l.)	1140	1443	1478	1235
Longitude (E^o)	13,8	7,4	7,3	6,3
Latitude (N^o)	66,7	61,8	60,6	60,1
Mass-balance measurements	1970-2020	1988-2019	1963-2020	1977-1981
Runoff observations	1969-2020	-	-	1963-2020

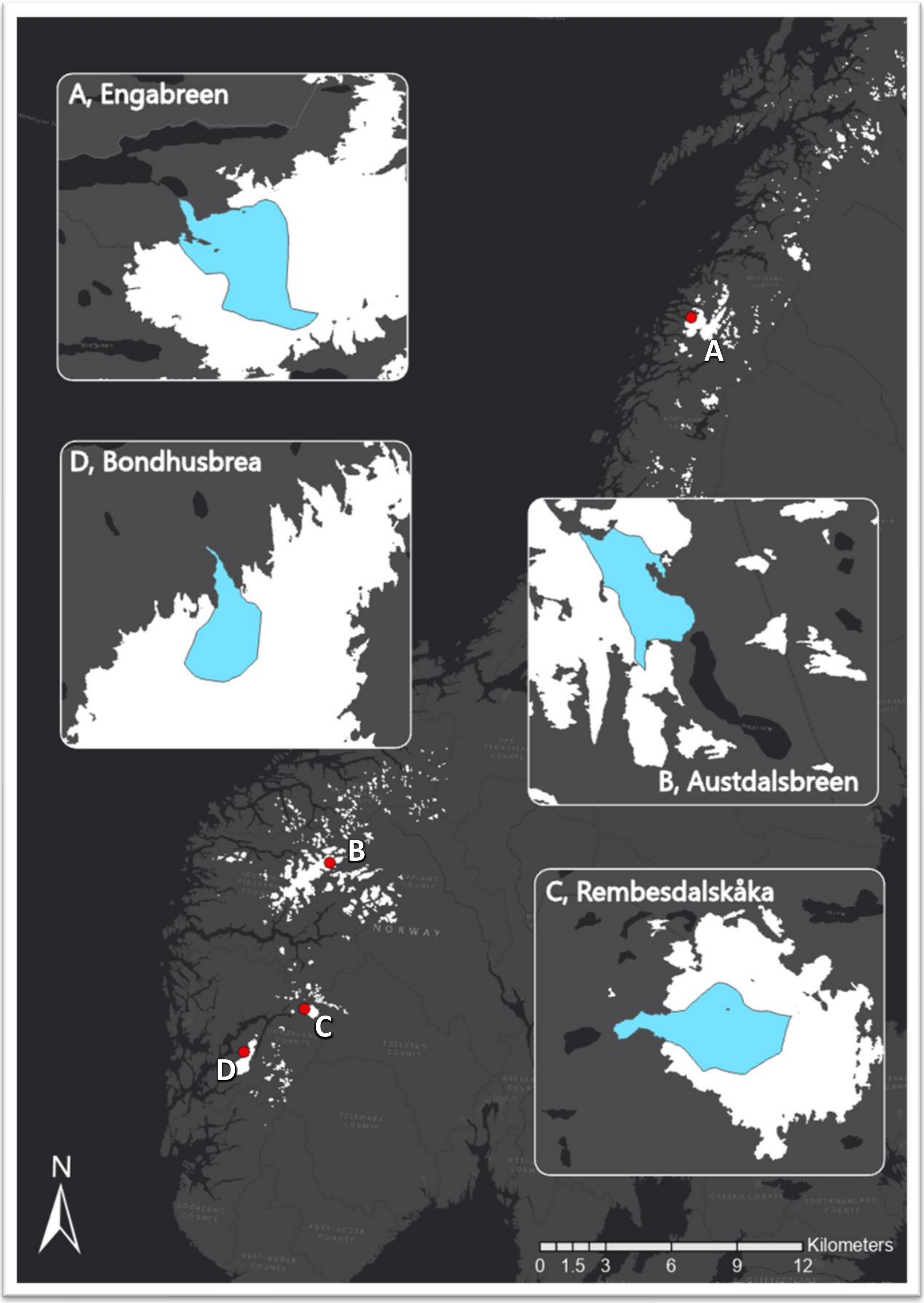


Figure 2 - Map of part of Scandinavia. Glaciers/ ice-caps of Norway are highlighted with white color and the four study sites are marked with red dots. In the detailed smaller maps, the certain glacier involved in this study are highlighted with light blue. Source of glacier outlines: NVE.

Engabreen (marked with A in Figure 2) is an outlet glacier of the Vestre-Svartisen icecap and one of Norway's best-studied glaciers. Documentation of the glacier length dates back to 1903, while mass balance measurements started in 1970. Glacier outlines (Figure 3) were created for four periods based on different mapping methods (Winsvold et al., 2014).A subglacial laboratory was built and set up in 1992 (Andreassen et al., 2020), simultaneously with the tunnel, which serves as an intake for the Svartisen Hydropower Station. Engabreen was once calving into the glacial lake, Engabrevatnet. However, the glacier retreated rapidly between 1931 and 1965. The last period Engabreen advanced was during the 1990s when the glacier front almost reached the shore of the glacier lake. Afterward, it shrank 300 meters in 10 years between 1999 and 2009 and an additional 236 meters until 2018 (Andreassen et al., 2020, Andreassen et al., 2012). Long-term measurements display a slight reduction (- 0,7 m w.e.) in the surface mass balance of Engabreen since the beginning of surveying mass-balance in 1970 (Kjøllmoen et al., 2019), which suggests that the glacier has been in balance despite the considerable retreat of its tongue in the ablation zone. Svartisen Hydropower Station began operating in 1993. It is one of the two hydroelectric stations that have an inlet channeling meltwater from directly under a glacier. The infrastructure includes a dam which creates a vast reservoir, Storglomvatnet, along with circa 100 km tunnel system (Statkraft hydropower plant factsheets), which transports water to the station from several lakes, reservoirs, and the sub-glacier tunnel under Engabreen.

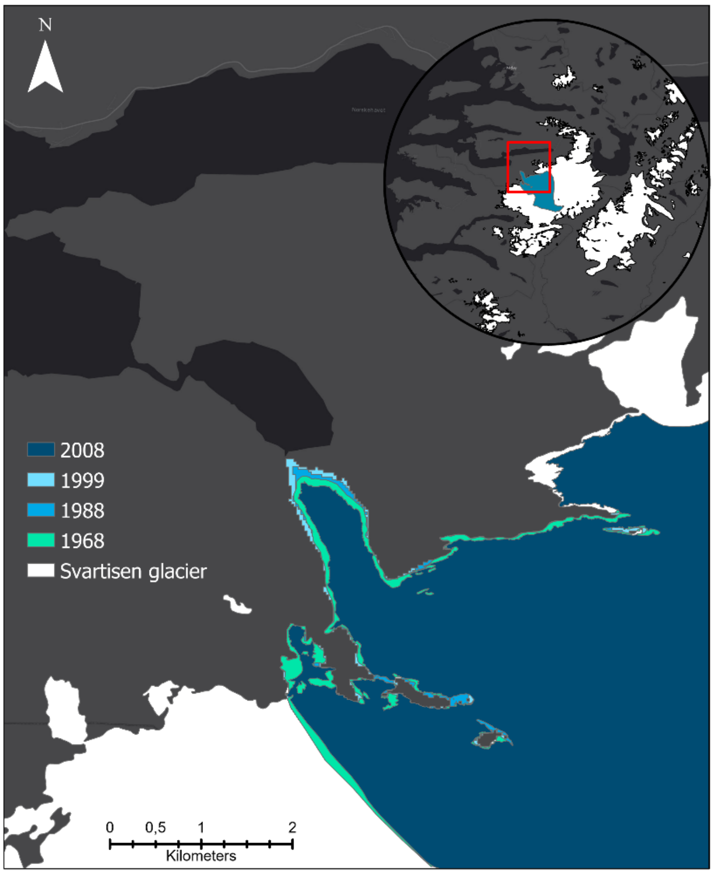


Figure 3 – Frontal positions of Engabreen since 1968. Source of glacier outlines: NVE.

Austdalbreen (marked with B on the schematic map) is a glacier arm of mainland Europe's largest icecap, Jostedalsbreen. Austdalsbreen terminates in a glacier lake, Stygavatnet, which became regulated in 1988. The regulation biased the ablation of the glacier front, which can cause biases that are not reflected in the mass-balance records (Andreassen et al., 2020). On the other hand, I received advice on involving Austdaslbreen since it carries a clear potential to investigate glaciers' impacts on run-off for catchments with connection to hydropower production. Moreover, mass-balance measurements were continually recorded for Austdalsbreen since the late 1980s, while glacier area data dates back to 1966 based on topographic maps (Andreassen et al., 2016). The Jostedal hydropower plant was established and began production in 1989 and is a regionally significant source of electricity. Stygavatnet, which is directly connected to the hydropower infrastructure through tunnels, is the most substantial water reservoir for energy production in the region.

Rembesdalskåka (marked with C on the schematic map) is a glacier arm of the Hardangerjökül icecap. As an individual glacier, Rembesdalskåka is the sixth-largest glacier all over Norway with 73 km^2. Demmevatnet - a glacier-dammed lake dammed by Rembesdalskåka - is an excellent example of natural hazards glaciers may pose to downstream communities. GLOFs (or jøkulhlaups) were a constant threat for local people of the Sima valley, which resulted in a deadly jøkulhlaup in 1893 (Elvehøy et al., 2002). Later the glacier lake that GLOFs drained into was regulated, preventing potential damage during the most recent (2014, 2016, 2017, 2018, 2020) and future GLOF events (Kjøllmoen et al., 2019). Mass balance investigations began in 1963 on Rembesdalskåka. The glacier has produced a remarkably negative cumulative mass balance since then. Significant retreat (more than 1,5 km) of the glacier tongue was assessed since the first documented length in 1916 with an advancing period in the 1990s (Andreassen et al., 2020). The glacier lake was regulated for hydropower production at Statkraft's Sima hydropower plant, which started generating electricity in 1980 and is the second-largest construction in Norway to date (Statkraft, 2010).

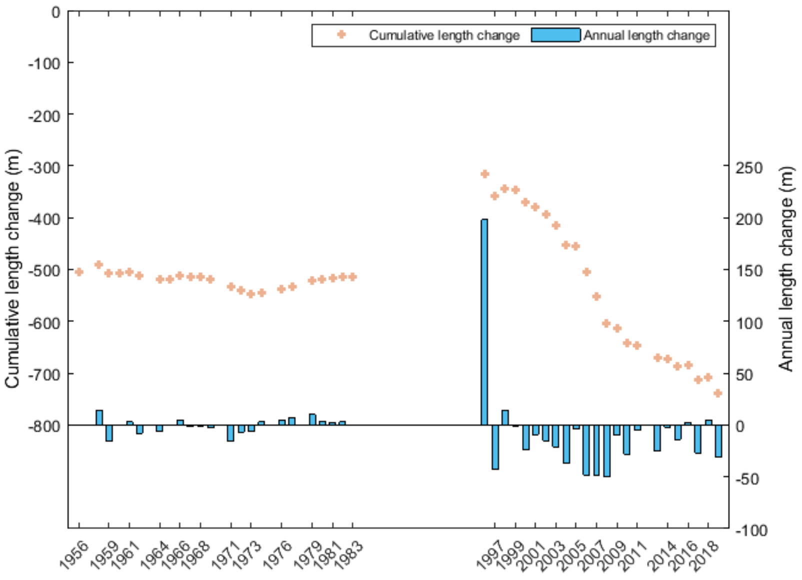


Figure 4 - Glacier front changes of Bondhusbrea.Cumulative changes refer to the retreat relative to the first measurement in the early 1900s, while annual changes represent yearly variations in the frontal position. Source of data: NVE.

The last glacier involved in this study is **Bondhusbrea** (marked with D in Figure 2), an outlet glacier of the Søndre-Folgefonna ice cap. Bondhusbrea is a relatively easily accessible glacier at the end of the Bondhus valley. This feature made Bondhusbrea a popular destination among both local hikers and tourists.

Frontal position change assessments demonstrate evident retreat since the turn of the century (Figure 4) following the advance showed during the 1990s. However, according to mass balance estimations performed by Andreassen et al. (2020), the South-Folgefonna plateau glacier has shown the least negative mass-balance in the last 20 years since the period of mostly positive annual mass-balances among Norwegian glaciers during the 1990s (Andreassen et al., 2020).

Statkraft's Mauranger hydropower station is benefitting directly from glacier melt through a sub-glacier tunnel under Bondhusbrea. Therefore, Bondhusbrea was deemed a suitable study site.

2. Scientific Background

2.1. Climate in Norway

Numerous climatic and topographic factors influence the climate of Norway strongly. Norway has an immensely long coastline rugged by fjords, and the country is divided by complex terrain (see Figure 6). Due to these factors, the climate varies greatly within the country's borders (see Figure 5). One can find a wet maritime climate along the coastline, whereas going more inland, the climate gets dryer, more continental (Andreassen et al., 2012).

As a result of the Gulf Stream, the temperature is considerably higher than the latitude would suggest, particularly along the coastline. The mean annual temperature across Norway has varied around + 1 °C. However, the temperature fluctuates widely with latitude, altitude, and climate continentality. Annual average precipitation over the whole country is approximately 1500 mm. Precipitation varies largely with geographic conditions as well. There is a sharp decrease in average precipitation from the west to east (Hanssen-Bauer et al., 2017), mostly caused by the shading effect of the Scandinavian mountain range.

In glacier studies, besides the amount of precipitation, seasonality and form are two other vital determinants. The seasonal distribution of precipitation is diverse in the interior, whereas there are less substantial variations in precipitation seasonality along the coastline (Hanssen-Bauer et al., 2017). In terms of precipitation form, snow is essential in studies focusing on glacier changes. Annual snowfall also varies extensively spatially. For instance, at Ålfotbreen, in the relative proximity of the coastline, the climate is predominantly wet maritime, and yearly total snowfall of up to 8-10 meters is common. While 200 kilometers to the east, at Gråsubrean, the mean yearly snowfall amounts only to approximately one-fifth of that of Ålfotbreen (Andreassen et al., 2012).

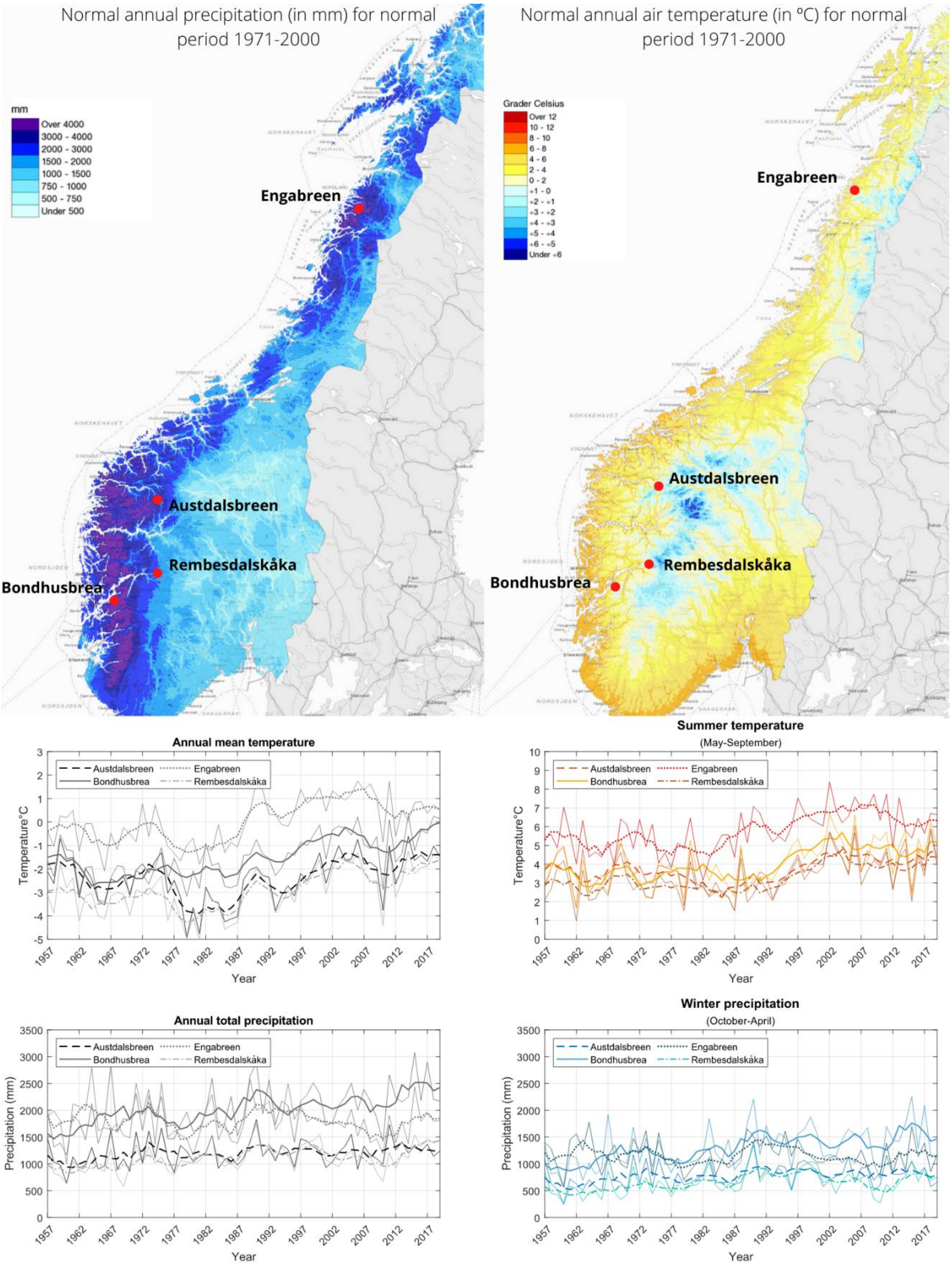


Figure 5 - Summary of climate in Norway. Maps show the normal anual precipitation and temperature for 1971-2000, while the graphs demonstrate a detailed exhibition of seasonal and annual temperature and precipitation in the ablation zone of the four studied glacier with the 5 year moving average included. Source of maps: http://www.senorge.no/

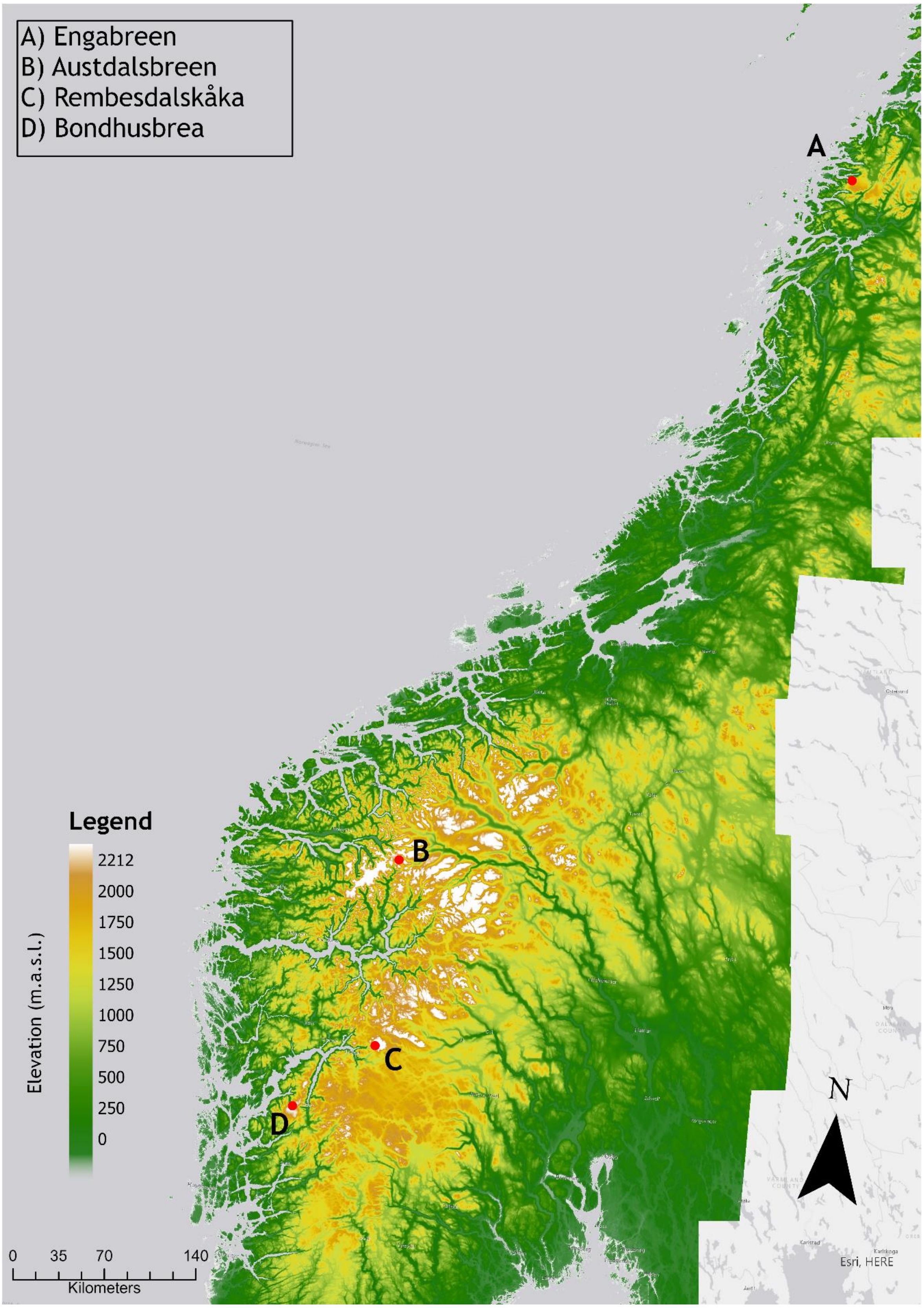


Figure 6 - Elevation map of Norway. Altitude is a major factor in local-scale climatology since it has a significant impact on both temperature and precipitation. Source of DEM: hoydedata.no

2.2. Glaciers in Norway

The most recent, and up to this date, the most comprehensive glacier inventory of Norwegian glaciers reports a total of 2534 glaciers, which covers an area of 2692 km^2 ± 81 km^2 (Andreassen et al., 2012). It is, respectively, the largest glacier coverage in mainland Europe within the borders of one country (Beniston et al., 2018).

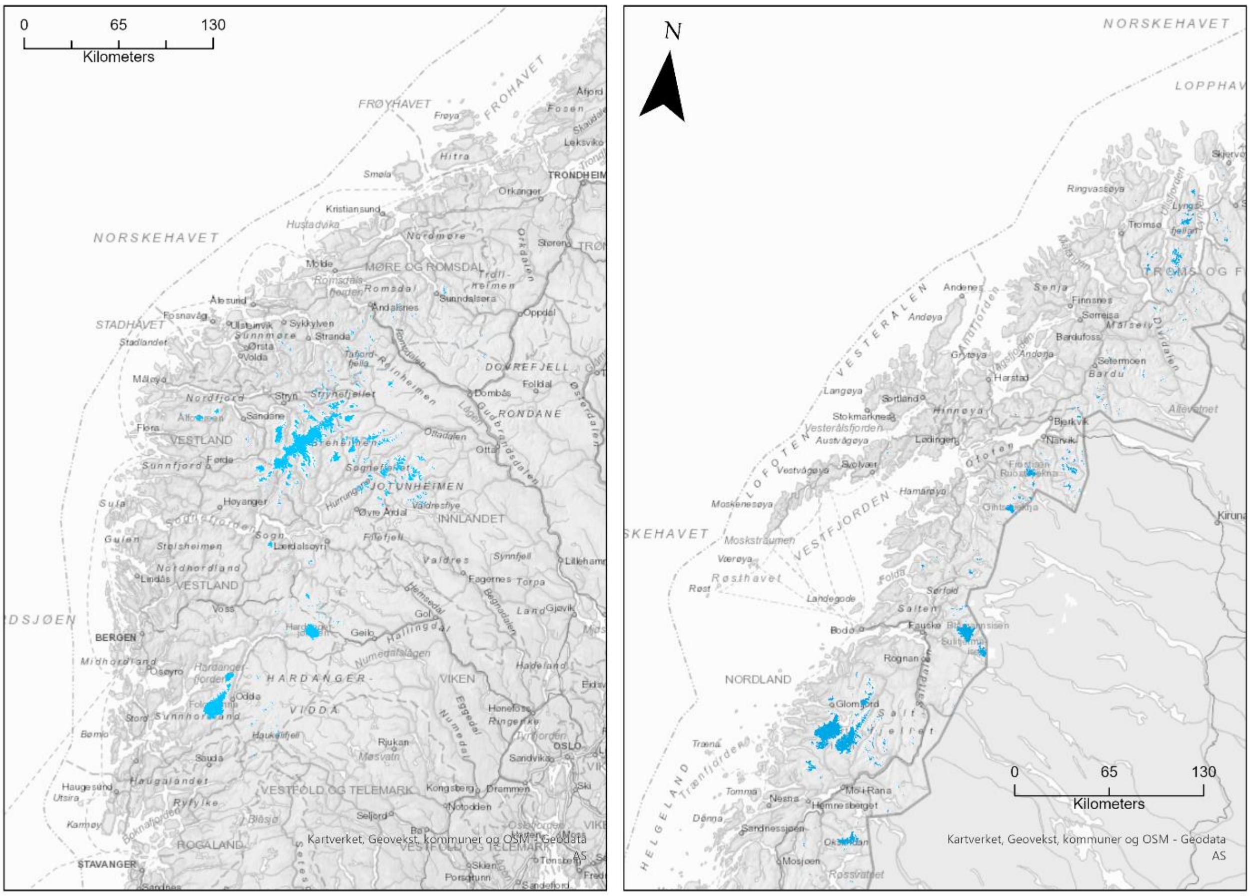


Figure 7 - Glaciers in Norway (marked with blue color), divided into two geographical regions, south (left) and north (right). Source of glacier outlines: NVE.

Glaciers are spread over in Norway, where the southern region accounts for 57% of the total glacier area, whereas the northern glacier region represents 43% of the total area covered with glaciers. The most extensive ice mass in Norway is Jostedalsbreen, which lies in the south. The Jostedalsbreen is subdivided into 82 smaller glacier units (Andreassen et al., 2012), including Austdalsbreen, which is one of the study areas in this paper.

2.3. Importance of Hydropower in Norway

Due to its topography and climatic conditions, Norway bears an immense hydropower potential in Europe. Hydropower holds a firm position in the Norwegian energy portfolio. Presently, 98%

of the annual energy production derives from hydropower in Norway (Gebremedhin and De Oliveira Granheim, 2012). Hydropower's advantage over other forms of renewable energy sources, such as wind and solar, is that hydropower carries huge storage potential – when paired with a reservoir -; thus considerable flexibility (Eurelectric, 2011). These features of the Norwegian hydropower systems lead to assumptions that Norway can take place in Europe as the continent's battery in the not too far future. This essentially means that hydropower will be used to balance out other types of renewables and vice versa in cooperation with European countries that generate a fair share of their electricity from renewable energy sources, such as the United Kingdom and Germany (Graabak et al., 2017). A report by the German Advisory Council on the Environment disputes the prospect of energy cooperation between Germany and Norway based on renewables and using subsea cables connecting the two country's grid systems (Environment, 2011).

Catchments regulated by hydropower infrastructure include 60% of Norway's total glacier area (Andreassen et al., 2012). Therefore, melt-water run-off from glaciers contributes substantially to the water resources utilized to generate electricity through hydropower (Engelhardt et al., 2014).

2.4.Background of Downscaling

Catchment-scale run-off modeling requires high-resolution climate data input in order to accurately model discharge in the basin. This subchapter discusses the theory of obtaining good quality spatially high-resolution climate data. Various techniques exist to downscale climate data to a finer resolution. Two primary downscaling schemes are currently used in practice; dynamical downscaling and statistical downscaling (Fowler et al., 2007). These methods can be grouped into two categories; nested models and empirical approaches (Raju and Kumar, 2018).

2.4.1. Dynamical Downscaling

Dynamical downscaling is the first method to be discussed, which derives from nested models. Regional Climate Models (RCM) are most commonly produced by downscaling General Circulation Models (GCM) by using this method (Fowler et al., 2007). In that case, the RCM is nested within the GCM, which means that the global-scale atmospheric features simulated by the GCM are integrated into the RCM within vertical and horizontal boundaries. Additionally, regionally applicable climate variables and other physical factors are considered when modeling climate on a local level (Trzaska and Schnar, 2014). Albeit dynamical downscaling is a highly advanced method with the potential to simulate small-scale physical features and often the more accurate out of the two techniques (Raju and Kumar, 2018).

Nevertheless, uncertainties remain. Such uncertainties can emerge from the biases carried by GCM that the downscaled RCM is forced with (Trzaska and Schnar, 2014). Moreover, dynamical downscaling is computationally hugely exceeding the statistical downscaling requirements (Wilby et al., 2009) and requires considerably more input.

2.4.2. Statistical Downscaling

Statistical downscaling is computationally a much simpler process than dynamical downscaling. The cluster of statistical methods is not homogenous and involves numerous techniques, such as regression models, weather schemes, and weather generators. In contrast to dynamical downscaling, statistical approaches often neglect complex physical, atmospheric processes when downscaling climate variables (Fowler et al., 2007). It is an empirical approach because the statistical procedure relies on an empirical relationship between a large-scale climate variable – a predictor, in other words - and local features or predictors (Trzaska and Schnar, 2014). Geopotential height – elevation – is a typically useful predictor (Fowler et al., 2007); thus, the correspondence between near-surface air temperature and altitude, for instance, fits perfectly into this category.

The downscaling method used in this study will be a two-step process following a similar procedure to Machguth et al. (2013). In their study, Machguth et al. first interpolated the climate data topography to a more satisfactory resolution using inverse distance weighting interpolation (Machguth et al., 2013). While secondly, the temperature was modified in alignment with elevation using temperature slope lapse rates. The same process applies to precipitation.

In this study, slight alterations were made to the method after testing three different interpolation methods in MATLAB. Cubic interpolation was deemed sufficiently effective and was more time and memory efficient than the other two proven techniques since it applied one of MATLAB’s in-built functions (see Section 3.4). In contrast to Machguth et al. (2013), and due to the lack of weather station groups suitable for calculating slope lapse rates (SLR), calculation of final SLRs used for downscaling temperature and precipitation is based on the national observational climate dataset, seNorge.

2.5. Background of Modelling Runoff in Glacierized Catchments

The contribution of glaciers to the total runoff in greatly glacierized catchments may exceed rain, especially during summer. According to research, approximately one-sixth of the population of the Earth relies on glacier meltwater as a primary freshwater resource (Hock et al., 2005). Furthermore, glaciers can strongly contribute to electricity production by providing inflow to hydropower plants, which aspect is vital in Norway, where 96% of the energy is produced through hydropower (Graabak et al., 2017). Hence, simulating streamflow and assessing the contribution of glaciers to the runoff in certain parts of the planet is crucial for water resource management and electricity production (Engelhardt et al., 2014).

Two common types of hydrology models used to simulate glacier meltwater discharge are energy-balance and temperature index models. The latter is prominently advocated due to its relatively low computational requirements. On the other hand, energy balance models are more enhanced versions of runoff modeling and take into account more physical processes and climate variables, making them more reliable for computing streamflow under a changing climate. However, a considerable limitation of such energy balance models is the numerous input data it requires. In parts of the world with insufficient data for, among others, wind speed, radiation, or temperature, energy balance models are not applicable. Naturally, the method needs to be chosen based on the objectives and purpose of the specific study it will be used in.

Nonetheless, the more complex processes, such as routing of streamflow on the glacier, glacier extent, change over time. The better the model will simulate discharge in glacierized basins. Therefore, Hock et al. (2005) recommend a nested approach, where an extensive range of climate change related alterations can be addressed.

In a research aiming to assess the contribution of glacier meltwater to streamflow in three largely glacierized catchments in Norway, Engelhardt et al. (2014) applied a complex melt-model that's core is a temperature index model and takes into consideration, among other factors, solar radiation, glacier area changes over time and delayed runoff depending on the surface it flows through. The simulations ran on a daily time scale using seNorge temperature and precipitation fields for the period of 1961-2015. Their findings reveal an increased contribution of glaciers to total discharge over the basin area from approximately 10% in the 1990s to 15%-30% during the 2000s, and while precipitation displays a reducing tendency in the course of the same period, total discharge in the catchments intensified by 10% - 20% suggesting that glacier discharge overcompensated precipitation (Engelhardt et al., 2014).

Such complex models exceed the scope of this thesis. Accordingly, a more straightforward approach, a Positive *Degree Day* (PDD) model, will be used, based on the work of Hallé (2020). The PDD model simulates the total of degrees above zero as an integral of positive air temperature over a given period (Seguinot, 2013). The model is based on the empirical relationship between air temperature and surface melt. It is assumed that a certain amount of melting takes place for every positive degree above 0 ^{o}C (Calov and Greve, 2005).

3. Methods

There are several varying methods for assessing the contribution of glacier melt to the total runoff. Some of them could be ruled out right away, as it did not suit the time and work range of a master thesis. The main challenge in glaciology is to fit the methods to the actual case and available data.

Ultimately, the methods described in this chapter can be divided into five sections: (1) the utilized datasets and their brief background in Section 3.1, (2) methods for assessing regional climate models in Section 3.2; (3) methods for analyzing the variation of temperature and precipitation in the four selected study sites in Section 3.2, (4) methods for downscaling climate data in Section 3.4, (5) the mechanisms of the positive degree-day model in Section 3.5, (6) and finally how impacts on the hydropower industry were incorporated into the study with interviews in Section 3.6.

3.1. Climate Datasets

In the process of achieving the research objectives of this study, numerous different datasets, such as climate reanalysis and observational climate data, digital elevation models, runoff observations, or weather station data were used obtained from both Norwegian and global sources. This section is dedicated to demonstrating the diverse collection of data used in this thesis.

3.1.1. seNorge 2.0

SeNorge is a freely available climate dataset produced through the collaboration of the Norwegian Water and Energy Directorate, the Norwegian Meteorological Institute, and Kartverket. The various data categories can be downloaded from www.seNorge.no.

The gridded observational data is the result of an interpolation of weather station data from more than a thousand weather stations all over Norway and in buffer zones following the Swedish, Russian and Finnish borders. As a result, temperature and precipitation data are available in a 1 km^2 spatial and 24h temporal resolution spanning over the period of 1957-2020 and being updated daily.

The gridded temperature and precipitation data of *seNorge.no* are produced by the Norwegian Meteorological Institute (MET). Since 2018, through an improved seNorge v.2, MET provides daily mean temperature, maximum and minimum daily temperature, and total daily precipitation. The observational temperature and precipitation datasets' foundation is an ever-expanding weather station system spread over all Norway and a statistical method called optimal interpolation of the raw observational data obtained from the weather stations.

This study's climate datasets compile daily precipitation, near-surface air temperature, and new snow data. All of the datasets mentioned above have a 24h temporal resolution (between 06:00 UTC of the reported data and 06:00 UTC of the previous day) and a 1 km2 spatial resolution.

The spatial and temporal distribution of weather station density is not consistent in Norway. Most of the stations were installed to monitor the climate of urban areas. There is also an apparent disparity between the northern and southern parts of Norway, with a higher density in the south. Hence, climate interpolations for scarce data areas, such as mountainous regions, especially in Northern Norway, carry more considerable uncertainty.

3.1.2. ERA5-Land

The ERA5-Land climate reanalysis creator, the European Centre for Medium-Range Weather Forecast (ECMWF), has a long-standing experience in developing high-quality climate products, including the ERA-Interim and ERA5 datasets. ERA5-Land is a new, state-of-the-art climate reanalysis aiming to focus on climate variables over land surfaces globally. A climate reanalysis refers to the combination of observations from various forms and resources and climate models coupled with the laws of physics, which together form a solid core for a comprehensive global climate dataset (Muñoz Sabater, 2019). Essentially, ERA5-Land is an enhanced version of the land component of ERA5, and in order to make it more effectively functional, non-land fields, such as oceans, are obscured. Furthermore, ERA5-Land operates on a sufficient spatial resolution of 9 km compared to ERA5, which is available in 31 km resolution. During the downscaling, topographic forcing and daily lapse rates were applies to correct for biases in climate variables with a known relationship with elevation. In terms of temporal resolution, ERA5-Land is produced in hourly and monthly intervals. Currently, ERA5-Land climate reanalysis is available for the time-frame of 1979 to the almost present day, while progress is underway to expand the dataset’s time range until 1950, which is expected to be published later in 2020 (Muñoz-Sabater, 2017).

In this study, the average monthly temperature and daily precipitation were downloaded and processed. Monthly total precipitation was then acquired by converting hourly values into a monthly sum in MATLAB.

3.1.3. Climate models

Predicting future variations in hydrology requires adopting climate model projections of fundamental climate variables, such as near-surface air temperature and precipitation.

Climate models, however, differ from each other in numerous ways. Climate models apply varying schemes and parameterizations for atmospheric processes, and naturally, this will impact projected future climate scenarios. Global circulation models (GCM) are large-scale numerical models describing the climate system's various processes globally. However, it results in typically low-resolution model output. Regional climate models (RCM) provide a higher resolution alternative to GCMs by dynamically downscaling GCMs to a regional level. RCMs implement locally applicable physical processes and often take into account local topographic conditions, for instance, land use. Nevertheless, boundary conditions – which refers to mechanisms that are not anticipated by the model and required to be artificially prescribed, such as solar radiation, surface changes, or deviations in the atmosphere - in RCM simulations are adapted from GCMs.

GCM specified boundary conditions are eminently important in Norway, as the various GCMs can produce, for instance, differing patterns of storm tracks in the North-Atlantic region, which have an immense impact on Norwegian climate. These deviations in large-scale GCM climate system descriptions are then transferred to the RCM simulations and affect the model output.

Climate model outputs produced within the Coordinated Regional Climate Downscaling Experiment (CORDEX) framework were adopted in this study. The CORDEX coordinated climate model ensemble and model assessment initiative was established in 2009 to provide accurate climate projections for every continental domain of the Earth in light of heavy climate change. The time-frame aimed to be addressed by CORDEX simulations ends in 2100. EURO-CORDEX is focusing on the European domain, including a narrow portion of North-Africa and Iceland. Regional climate model simulations are, in contrast to other domains, also produced in a 12 km (0.11 degrees) grid structure and in the uniform 50 km (0.44 degrees) as all the other domains in CORDEX (Jacob et al., 2020).

The optimal manner to adopt such climate projections for run-off modeling would be to use several GCM-RCM combinations. Nonetheless, considering the scope of a master thesis and the study's objectives, it would not have been feasible to work with numerous different models. Eventually, one regional climate model, RCA4, was selected nested within the EC-EARTH GCM. The model selection is based on previous studies evaluating model performance over

Scandinavia (Landgren et al., 2014, Dyrrdal et al., 2018). The original model output of near-surface air temperature and precipitation and three different bias-adjusted versions of the regional climate model RCA4 for future greenhouse gas concentration scenarios Representative Concentration Pathway (RCP) 4.5 and 8.5 were downloaded from https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl/.

3.1.3.1. EC-EARTH General Circulation Model

EC-EARTH is an advanced Earth system model (global climate model) based on the numerical weather prediction system of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hazeleger et al., 2012). The European EC-Earth consortium developed the model with the leading role of the Swedish Meteorological and Hydrological Institute (SMHI). Coupled physical and biogeochemical processes are taken into consideration when describing large-scale global climate patterns. EC-EARTH has several model components for defining various physical processes, such as the atmospheric circulation model, ocean model, vegetation model, and ice sheet model (SMHI, 2015).

3.1.3.2. RCA4 Regional Climate Model

The most recent version of the Rossby Centre regional atmospheric model (RCA) is used in this study for projecting future run-off trends in the study areas. The RCA4 regional climate model initially relied on the numerical weather prediction model HIRLAM (Undén et al., 2002). The major with earlier versions of RCA (up to RCA3) was that although it was applicable globally, the model was practically tuned for Europe. Hence the most substantial change in RCA4 is the inclusion of global databases such as the ECOCLIMAP (Masson et al., 2003) for land-use and vegetation, Gtopo30 (USGS, 1996) for topography, and some other new additions (SMHI, 2015). Moreover, numerous physical parameterizations have been upgraded to better fit the model for global climate modeling purposes (Strandberg et al., 2014). A comprehensive description of earlier versions of the RCA model is presented by (Rummukainen et al., 1998, Rummukainen et al., 2001, Räisänen et al., 2003, Räisänen et al., 2004, Jones et al., 2004, Kjellström et al., 2005, Samuelsson et al., 2011).

3.1.3.3. Bias-Correction Methods

Bias-adjustment of GCM and RCM simulations is strongly recommended to increase the models' accuracy for examining the impacts of climate change on a local scale (Landgren et al., 2014). Improving projections of various climate variables is also essential for examining changes in hydrology and its possible impacts on humanity (Yang et al., 2010). Hence, three bias-corrected versions of the EC-EARTH - RCA4 GCM-RCM combination were assessed, and the best performing model variant was selected for modeling future runoff.

The Distribution-Based Scaling (DBS) approach was specifically developed to enhance the usability of RCM projections for assessing the effects of climate change on hydrology and ensuring the viability of using RCM derived temperature and precipitation as input in hydrology models. The technique was first presented by Yang et al. (2010) for correcting hydrologically essential climate variables obtained from the RCA3 regional climate model to match the distribution demonstrated by observational data. The DBS method applies two different distribution approaches for temperature and precipitation since temperature displays a more uniform distribution compared to precipitation. Firstly, the number of wet and dry days is rectified by defining a locally and seasonally dependent cut-off value for precipitation, which is then considered the threshold for wet and dry days. Days with larger modeled total precipitation than the defined threshold are then regarded as wet days, whilst days that do not reach the threshold are dry days. Following the first step of adjusting wet and dry days, a gamma distribution approach is applied to alter modeled precipitation to better match the distribution of observed precipitation. Since temperature is more equally distributed, it can be described by a normal distribution function. The correlation between temperature and precipitation is taken into consideration; thus, distribution parameters are described by the specific state of the day (dry or wet) to adjust modeled temperature series to observational distribution (Yang et al., 2010). The appraised variability and mean of the original RCM output remain unchanged after the bias-correction.

The second and third bias-adjustment approach are two slightly different versions of the Cumulative Distribution Function Transform (CDFt), which, similarly to the DBS method, attempts to optimize the distribution of a modeled climate variable to match observed variables more precisely (Vandeskog et al., 2020). The CDFt scheme was first developed to downscale GCM simulated wind-speed, and it assumes that the cumulative distribution of an RCM climate variable can be fine-tuned to suit observations better by defining a transformation value that will allow the correction (Michelangeli et al., 2009).

3.1.4. Run-off Observations

Runoff data will be used to validate the output from the Positive Degree Day Model. Water-level is measured and collected at gauging stations, and it is stored in an hourly (or more frequent) temporal resolution in a database managed by NVE. Water level data then converted into water flow volume in m^3/sec. Throughout Norway, around 600 stations are installed. Around 200 of these stations are directly owned by NVE (NVE website - reference). Runoff observations were used to validate the PDD model's ability to simulate monthly discharge in the basin. Adequately long-term observations are available for two glaciers included in this study, Bondhusbrea and Engabreen.

Since the observational runoff data is not freely available, it was provided by NVE upon request for Engabrevatnet (1981-2019) and the Engabreen subglacial tunnel (1998-2017), and Bondhusbrea (1981-2019). The tunnel beneath Engabreen was opened in 1993 to facilitate hydropower energy production at the Svartisen power plant. Even though discharge is measured in the meltwater outlet, additional uncertainties may arise when using the downstream runoff observations from the station at Engabrevatnet after the tunnel was opened for model validation. Therefore, the model performance assessment will be quantified solely from 1986 through 1993 before opening the artificial meltwater tunnel. The other study site with long-term contiguous discharge observations is Bondhusbrea. However, a subglacial tunnel drains meltwater of Bondhusbrea. There is no available inflow data for the sub-glacial tunnel, making runoff observations at Bondhusbrea ineligible to precisely validate model performance. However, the PDD model's ability to catch seasonal variations in discharge can be validated against direct observational data at Bondhusbrea as well.

3.1.5. Glacier Features

Mass balance

The glacier department of NVE is currently responsible for developing mass balance records for glaciers in Norway. Mass balance measurements began in 1949 on Storbreen, in the Jotunheimen region. In the coming decades, the mass balance has been estimated at 42 glaciers. However, it is still only less than 15% of the total glacier-covered surfaces measured, and in most cases, for relatively short periods (< 10 years). As in 2010, mass balance measurements took place on 15 glaciers in Norway, comprising circa 7% of the country's total glacierized area (Engelhardt et al., 2012, Andreassen et al., 2016). In 2018, NVE measured the mass balance of ten glaciers in Norway.

NVEs surface mass balance records are a result of different field and post-processing methods. Winter balance is measured at the end of the accumulation season around April or May. The prominent manner which is used during these field investigations is probing against the summer surface along with a specific profile or grid to determine snow depth and verifying the probing with stakes where possible as stake density varies from glacier to glacier with a mean of 5-15 stakes (Andreassen et al., 2016). Snow density is measured in snow pits at different elevations. Summer mass balance field investigations are often performed after the ablation period in September or October with stakes. The annual balance is the difference between winter and summer balance and represents the period between the end of two consecutive summer melting seasons (Kjøllmoen et al., 2019).

During post-processing, these point-based field measurements were interpolated to represent the whole glacier by area-averaging the values with a profile method. A summary of the profile method provided by Andreassen et al. (2016): "In the profile method, the point measurements vs. altitude are plotted, and interpolated balance profiles are drawn to obtain mass balance values for each altitudinal interval. The elevation of point measurements and area distribution is taken from the most recent map/digital terrain model of the glacier".

Length changes

Glacier length measurements started in Norway kicked off in 1899. At the moment, NVE is responsible for collecting glacier length data as well. Since the beginning of the investigations, more than 70 glaciers' advance or recession has been observed. The selected glaciers in this study all have more than 50 years long length change records. The current monitoring network consists of 39 glaciers, which accounts for roughly 14% of the total glacier-covered area in Norway (Kjøllmoen et al., 2019).

The annual length change is calculated by measuring the distance between the glacier terminus and one or more reference points taken during earlier measurements. In rare cases, independent civils carried out length change documentations, some of which were later added to the already existing NVE series (Kjøllmoen et al., 2019). Besides, remote-sensing derived center lines can verify long-term in situ front position measurement where possible. NVE generated these center-lines using aerial images and satellite imagery, and digital elevation models for glaciers bigger than 1 km^2. Glacier length changes were then measured by assessing the distance between the terminus and the highest point of the centerline of a glacier (Winsvold et al., 2014).

3.1.6. Spatial Datasets

Glacier outlines

Historical glacier outlines were compiled by NVE using various methods since the available material varied from time to time. In principle, NVE assembled their glacier outline inventory using three datasets for 1947 to 1985, 1988 to 1997, and 1999 to 2006. For glacier extents of the earliest period, paper topographic maps derived from aerial photos were digitized, georeferenced, and used to create the outlines between 1947 and 1987. Historical analog topographic maps were digitized, georeferenced, and included in the analysis to extend the inventory's time frame and complement the orthophoto-based glacier outlines. After introducing high-resolution satellite imagery in the 1970s, it became an utterly suitable manner to construct glacier extents of remote areas. NVE used modern multi-spectral Landsat TM/ETM+ satellite imagery to produce the glacier extent outlines of Norwegian glaciers through a GIS-based procedure, following the Global Land Ice Measurements from Space (GLIMS) guidelines. The reason for choosing Landsat imagery is that their sensors cover a much larger area than other satellites that would otherwise fit the task of glacier monitoring, making the processing procedure a lot quicker by focusing on larger areas at the same time. The relatively wide range of time of the 1988-1996 and 1999-2006 datasets is due to the difficulties of finding cloud-free Landsat satellite imagery for all Norwegian glaciers in the same year or a couple of years apart, which is most likely the result of the country's climatic conditions. As a conclusion of NVE's comprehensive mapping work, the latest glacier inventory provides us with outlines for all Norwegian glaciers.

Glacier outlines are used to visualize spatial changes and calculate area loss of the glaciers studied in this thesis. Furthermore, glacier outlines will be used as input raster files in the PDD model to distinguish climate variables applicable to the glacier area only.

Catchment outlines

NVE created and have maintained a comprehensive catchment database, called REGINE (REGIster over NEdbørfelt), where basins are divided into several sub-fields and have an assigned ID based on their level in the catchment system. The catchment barriers and borders are based on the paper map series 'Norway 1:50 000' of the Norwegian Mapping Authority. The spatial data is freely available for the broad public on the website *temakart.nve.no/tema/nedborfelt*. The catchment outlines will be used as catchment masks in the PDD model to limit the model's specific outputs to the desired area.

3.1.7. Digital Elevation Models

Norwegian DTM 10 Digital Elevation Model

To account for elevation-related biases in temperature and precipitation during the downscaling process of the seNorge climate dataset, a digital terrain model (DTM) was used, which is freely available in the map catalog of the Norwegian Mapping Authority. The DTM, in its current state, covers the whole of mainland Norway with a grid size of 10 m x 10 m and uncertainty of +/- 1 m. The elevation model was obtained through laser-scanning of the surface, which is carried out by planes. By the end of 2019, an area of 186.000 km2 of the planned 230.000 km2 has been laser scanned. The DTM is referenced to Norway's official coordinate systems, EUREF UTM zone 33; thus making it perfectly compatible with the seNorge dataset, which uses the same coordinate system (Kartverket, 2019). The data is available in raster format at https://kartkatalog.geonorge.no/ and was processed in ArcGIS after downloading. The DTM tiles were downloaded for specific regions of Norway and clipped afterward to the particular study areas it will be used for.

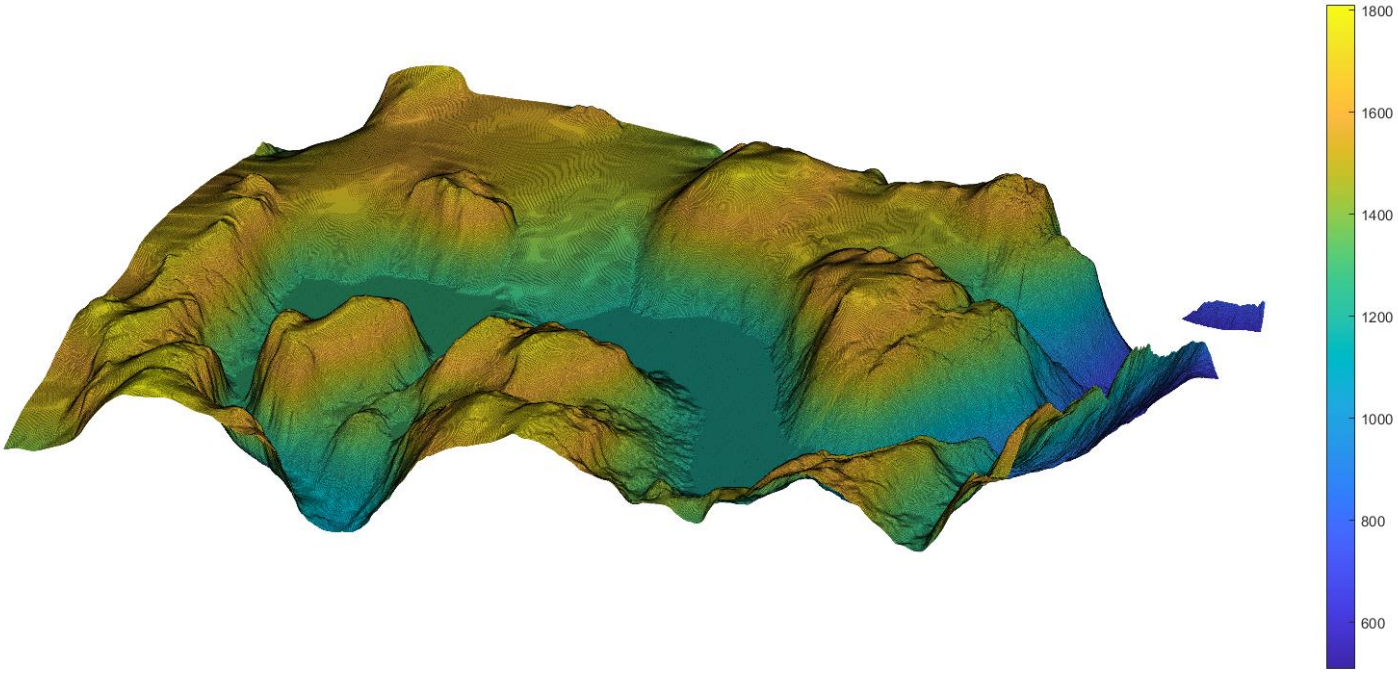


Figure 8 - Digital Terrain Model in a 10 m resolution around the glacier of Austdalsbreen. Source of data: https://kartkatalog.geonorge.no/ metadata/dtm-10-terrengmodell-utm33-2019/

ASTER Digital Elevation Model

The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (DEM) covers 99% of Earth's surface. It was first released in 2009 due to a collaboration between the Ministry of Economy, Trade, and Industry of Japan and the United States National Aeronautics and Space Administration (NASA). The imagery needed to produce the digital elevation is captured by the ASTER equipment on the board of the joint USA, Japan, Canada operated Terra satellite system. The ASTER digital elevation model is available in 30 m x 30 m resolution and is free to download from https://earthdata.nasa.gov/ (Aeronautics and Administration, 2019). The ASTER DEM involvement was made necessary because, after the first couple of downscaling tests of ERA5-Land, it was evident that the process would produce a more precise and smoother outcome when the DEM in the process is referenced in the same coordination system (WGS84).

3.2. Methods for Data Analysis

This subchapter describes how daily temperature and precipitation data obtained from the seNorge Norwegian observational climate dataset was processed and used to analyze climate fluctuations throughout the selected study sites and estimate correlation with glacier changes temporally and spatially. In addition, the evaluation of glacier changes is based on the comprehensive glacier database of NVE, freely available on https://www.nve.no/hydrology/glaciers/glacier-data/ (Andreassen et al., 2012, Andreassen et al., 2016, Winsvold et al., 2014, Kjøllmoen et al., 2019)

3.2.1. Methods for Exposing Climate Trends

The future contribution of glaciers to catchment runoff will be extensively biased by climate-change. Therefore, the thesis's primary goal is to identify past climate trends and predict what the future holds for certain glacier regions of Norway, considering that climate can be influenced by several factors, such as distance from the coastal topography.

The study focused on analyzing the climate trends on each study site's ablation zone since this section of the glacier contributes most to the runoff. In order to identify the ablation zone, elevation line altitudes (ELA) were used. The data was available for every glacier in the study. Since the ELA is not a consistent line over a glacier and several factors can influence its position inter-annually, the average ELA of the last ten years (where available) was calculated and used to determine the extent of the ablation zone of the glaciers involved in the study. Once the ablation zone was designated, the observational gridded precipitation and temperature data were downloaded manually from *seNorge.no* by following contour lines on the base map of the download website. Despite aiming to be as precise as possible, this approach comes with uncertainties. Visible borderlines for each grid cell would have eliminated this issue.

By the end of the downloading process, the daily temperature and precipitation data for the time-range of 1957-2019 were ready to be read into MATLAB and processed. The data were downloaded in comma-separated text format tables (.csv). The comma-separated text was converted to numeric values with the' Text to Columns' function in Excel. The first column was converted to date category. The process was repeated for every downloaded table, which resulted in a coherent set of climate data for every glacier. In MATLAB, the consistent outlay of the data tables made it possible to generate an automatic function to read in all the tables. Once the tables were imported, they were merged using the `join` function and using the dates row (the first column in every table) as a focal point to concatenate the tables.

Seasonal temperature and precipitation variations are vital features in glaciology. Temperature and precipitation of the summer and winter seasons were extracted from the table created in the previous step. Firstly, an additional column was added to the table, containing the numbers of the month of the year, by using the `month` function in MATLAB. This step creates a logical index array, with values of 0 or 1, where 1 represents the row in the table that fits the determined criteria. In this case, the criteria were that the newly added month value had to fall into the 5, 6, 7, 8, 9 categories for selecting summer season and 10,11, 12, 1, 2, 3, and 4 in case of the winter season. The numbers represent the ordinal number of months in a year (1 = January, for instance). In earlier studies, ablation season focusing on runoff modeling was determined as May-September, whereas the winter season is naturally longer in Norway and stretches from October to April, particularly in the northern and mountainous parts of the country (Engelhardt et al., 2014). In the next step, solid and liquid precipitation were distinguished. The fluctuations of snow and rain ratio over time can be valuable information to determine what the future holds for glaciers. Following the recommendation of an expert actively contributing to the HBV-model of NVE, a temperature threshold was set at 0.5 ^{o}C. Precipitation that falls on days when the average temperature was higher than this threshold was considered rain, while precipitation measured on days with the temperature below the threshold value was regarded as snow. Yearly summer and winter mean and annual mean temperature besides seasonal precipitation was then produced using the `retime` function.

3.2.2. Methods for Analysing Glacier Changes

Mass balance

The mass balance data used in this study were downloaded from NVE’s glacier database (http://glacier.nve.no/glacier/viewer/ci/no/) in csv. format. Long-term mass balance measurements are available for three out of the four glaciers in this study.

The text-based tables were imported into MATLAB for further analysis and visualization. The data contains summer balance (Bs), winter balance (Bw), annual balance (Ba), and elevation line altitude data produced with different methods (see Section 3.1.5).

In order to understand climate-glacier interaction, mass-balance was plotted together with temperature and precipitation datasets in a tiled layout. The Bs, Bw, and Ba were plotted as stacked bar graphs in the first subplot, while winter, summer, and annual mean temperature were plotted in the second tile, and lastly, precipitation occupies the last subplot, since these are the major factors, among other less significant ones, that can influence glacier volume and area variations.

Length change

Similar to mass-balance records, glacier length measurements were downloaded from NVE glacier database - http://glacier.nve.no/glacier/viewer/ci/no/ - in csv. format. The data compiles of annual length change and cumulative length change, beginning with the year of the first measurement. In this case, the data do not need too much processing. The annual length changes were plotted as a bar graph.

3.3.Methods for Evaluating Regional Climate Model Performance

One of the main aims of this study is to provide a possible future runoff scenario and estimate the contribution of glaciers to discharge in highly glacierized catchments in Norway with hydropower production. The purpose is to appraise the potential impacts of shrinking glaciers on the Norwegian hydropower industry during the next decades. There are numerous climate projections available today to simulate future climate patterns. Regional climate models represent an enhanced, spatially higher quality alternative to global circulation models. This section will present the methods for evaluating the selected regional climate model and its three bias-corrected outputs.

The evaluation of the performance of RCA4 was performed by comparing it to observations in the reference period of 1979-2019. Since there are very few weather stations (WS) carrying sufficiently long observational records temporally, observations do not cover the reference period contiguously. Thus, WS observations cover various portions of the reference period (see Table 2).

Monthly observational weather variables (temperature, precipitation) were downloaded from seklima.met.no in *.xlsx* format and read into MATLAB by using the `readtable` function. Corresponding weather station coordinates were adopted from www.seNorge.no. Regional climate model data was downloaded from one of the official data nodes of the CORDEX project, https://esgf-node.ipsl.upmc.fr/search/cordex-ipsl/, in Network Common Data Format (NetCDF). Near-surface air temperature and precipitation were downloaded for the European CORDEX domain in a 0.11^{o} (~ 12 km) spatial resolution and in daily temporal resolution. The data was first read into MATLAB using the `ncread` function. However, the time variable was in `datenum` format and first needed to be converted to common datetime format using the `datenum` and `datetime` functions of MATLAB. After transforming numerical time values into common date time values, monthly mean temperature and monthly total precipitation was then calculated from daily values by implementing a ’for loop’ in order to compute mean values for every unique month, taking into consideration inconsistent number of days in months and leap-years.

Table 2 - List of weather stations used to assess regional climate model performance in Norway. In the variable column, T stands for temperature, whilst Pr represents precipitation.

WS	Location	Variable	Period	Lon	Lat	Elevation (m)
Bråtå - Slettom	Austdalsbreen	T, Pr	1991 – 2019	7.89	61.89	664
Bjørkehaug	Austdalsbreen	T, Pr	1984 – 2003	7.27	61.66	305
Rosendal	Bondhusbrea	Pr	1979 – 2019	6.04	59.99	75
Omastrand	Bondhusbrea	T, Pr	1979 – 2001	5.97	60.22	2
Folgefonna skisent.	Bondhusbrea	T	2016 – 2019	6.43	60.23	1212
Glomfjord	Engabreen	T, Pr	1979 – 2019/ 2002	13.98	66.81	39
Glomfjord skihytta	Engabreen	T, Pr	2015 – 2019	13.95	66.83	520
Finsevatnet	Rembesdalskåka	T	2006 – 2019	7.53	60.59	1220
Finse	Rembesdalskåka	T, Pr	1979/ 1983 – 1990	7.50	60.60	1223
Liset	Rembesdalskåka	Pr	1979 – 2010	7.27	60.43	748
Midstova	Rembesdalskåka	T, Pr	2012 - 2019	7.28	60.65	1162

After converting every climate variable into a monthly mean or sum, RCM evaluation against observation took place. Firstly, the closest RCM grid point had to be located. This step was implemented by identifying the smaller distance between RCM and WS coordinates. The minimum distance index in both dimensions was determined, and the variable was extracted from the RCM data matrix by applying the logical indexing technique. Once the climate variable was obtained for the nearest grid cell to the WS location, observational data and the simulated climate were plotted on the same plot. In addition, a statistical test provided further possibilities to evaluate model performance.

Root mean square error test

The root mean square error (RMSE) statistical analysis is a proven method in climatology to assess model performance. The root mean square error identifies the standard deviation at every residual (Rogerson, 2006). Residuals are a measure of how far each point of the data falls from the line of best fit (regression line). RMSE practically assesses the spread of the residuals and hence describes the concentration of data points around the regression line (Glen, 2020). The RMSE method as implemented in MATLAB:

```
RMSE_CM(m,1) = sqrt(nanmean((CM_temperature - AWS_temperature).^2));
```

3.4.Downscaling of Climate Data

Throughout this chapter, the emphasis will be on how both seNorge and ERA5-Land temperature and precipitation were downscaled to finer resolution using a simple statistical downscaling technique. Firstly, the climate data was interpolated to high resolution, and finally, it was adjusted using digital elevation models to account for elevation.

3.4.1. Calculating Slope Lapse Rates

The first step of the downscaling process is to calculate slope lapse rates (SLR). In order to obtain the most accurate outcome of high-resolution temperature and precipitation, several SLR were tested. Nonetheless, the method of calculating SLR from various sources remained the same throughout the whole procedure. Where reliable weather station data exists, SLR computations were carried out based on WS observations. However, it only applied to one study site, Engabreen, in Northern Norway. Three weather stations close to each other, at different elevations along the coast, in the proximity of Engabreen were used to calculate SLR. In addition, both original ERA5-Land and seNorge gridded data were tested for calculating SLR over a relatively larger area around the study sites. Moreover, where applicable, slope lapse rates retrieved from the literature were tested to examine the downscaling procedure's performance with different SLR values. Lastly, a monthly SLR was involved based on seNorge, solely to analyze how it improved downscaling performance compared to a static SLR.

Weather station based SLR

Monthly temperature data observed at Glomfjord weather station triplet was downloaded from seklima.no for the past five years and pre-processed in Excel. Related elevation values were obtained for each weather station and saved in an excel spreadsheet. In MATLAB, both excel files were read in as vectors. The annual mean, summer, and winter slope lapse rates were then calculated by assessing the relationship between altitude and temperature using linear regression. The functions `polyfit` and `polyval` serve this purpose in MATLAB. The polyfit function fits the data to a polynomial curve and determines the degree of the slope, whilst the polyval function measures the polynomial at each elevation – temperature pair. The SLR is practically the degree of the slope determined by the polyfit function, for instance a calculated slope of – 0.055 translates to a decrease of – 0.55 °C/ 100 m in temperature.

Precipitation observations were only available for one of the three weather stations; hence it was not feasible to estimate SLR for precipitation applying WS data.

ERA5-Land and seNorge based SLR

The principles were the same for calculating slope lapse rates based on climate reanalysis (ERA5-Land) and statistically interpolated observational climate data (seNorge). However, instead of only estimating the relationship between elevation and temperature at a couple of locations, a larger sample of grid cells was utilized to compute SLR. Every grid cell in ERA5-Land and seNorge has a corresponding altitude value. Using the `polyfit` and `polyval` functions in MATLAB, the relationship was assessed at every location for the timeframe of 2015-2019.

The final output of the SLR calculations are displayed in Table 7 and spatial variations of temperature lapse rates across Norway will be discussed in detail in Section 4.3.1.

3.4.2. Methods for Downscaling Climate Data

The main objective of climate downscaling is to obtain a higher resolution and generally better performing dataset, in better agreement with observations, than the original. As discussed in Section 2.4, numerous downscaling methods exist with diverse prerequisites. Considering the aims and scope of the thesis, the decision fell on a statistical downscaling method. The downscaling implicates the topographic factor using temperature lapse rate to account for alterations in near-surface air temperature and precipitation with altitude increases. Norway has complex topographic features such as fjords, narrow valleys, and 1500 meter high peaks in a swiftly changing landscape. In such circumstances, altitude becomes a vastly influential factor determining air temperature and precipitation at different elevations; hence it is crucial to incorporate topography elements into the downscaling process. Digital elevation models (DEM) offer the best possibilities currently to implement the downscaling. As a result of using DEMs, ERA5-Land was downscaled to a 30 m resolution using global ASTER DEM, while seNorge was downscaled to a fine resolution of merely 10 m utilizing the national digital terrain model. Consequently, the resolution of the DEMs determines the highest possible resolution that the data downscaled to.

The downscaled was implemented in MATLAB. The process required the following input data: original ERA5-Land and seNorge temperature and precipitation data, climate data topography, the earlier mentioned DEM products, and the previously calculated SLRs. As the first step of the downscaling, the original climate data is being clipped to the desired area, in this case for an area that involved both the actual glacier and at least three weather stations in order to be able to validate the output of the downscaling. In the case of seNorge, the handling of the fine resolution downscaled dataset required too much memory and the PC provided by NTNU was not able to deal with it. Therefore, albeit it became more time-consuming, the climate data was clipped separately to the glacier area and each WS.

Next, the DEM coordinates are used to find the nearest neighboring grid points in the climate data. After testing three different interpolation methods, the best performance was provided by the cubic interpolation technique. The in-built MATLAB function of `interp2` with a 'cubic' option was used to downscale temperature and precipitation. This method was the least time and memory consuming, which resulted in a smooth, adequate resolution output. Afterward, the climate data elevation is resampled by using the same steps as for the interpolation of temperature and precipitation fields. The new high-resolution topography is then extracted from the DEM elevation, and the resulting difference is multiplied by the SLR; thus, accounting for the increase/ decrease of climate variables with altitude:

```
Downscaled_data = (DEM – climatedata_topo) * SLR +
                original_temperature;
```

3.4.3. Methods for Validating Downscaling

In order to assess the quality of the downscaling process, the new, high-resolution temperature and precipitation were compared to observational data. The weather station was accessed from seklima.no, and coordinates were obtained from seNorge.no. Downscaled climate variables, ERA5-Land/ seNorge coordinates, and weather station data with corresponding coordinates were read into MATLAB. Following the import of data, the points of the downscaled data that fall closest to each weather station were singled out, using the following script in MATLAB:

```
dist = sqrt(latdif.^2 + londif.^2)
```

Once the closest points were determined, the original climate data, the downscaled version of it, and the observational data were plotted against each other in the reference period of 2015 – 2019 using the in-built `plot` function of MATLAB.

3.5. Methods for *Positive Degree Day* (PDD) model

The PDD model used in this study is a modified version of the temperature-index model developed by Danielle A.M. Hallé, a fellow master's student at NTNU. Hallé (2020) studied glaciers in Greenland and investigated the viability of glacier meltwater as a drinking water source in the future. An adapted version of the model mentioned above was used in this thesis, as it is suitable address the research questions adequately.

The objective of using a PDD model is to examine the volume past, and future runoff regimes in glacier dominated catchments in Norway and estimate the direct contribution of glaciers to the total discharge. The model consists of three main components. The first part computes the positive degree day sums, the next is responsible for calculating snow and ice melt in the catchments, while the final part converts it to total discharge.

3.5.1. PDD sum

The PDD sum is essentially the aggregate of temperature above the effective melt threshold (0 °C) during a certain period (Wake and Marshall, 2015). In her thesis, Hallé (2020) examined the performance of three different methods for calculating PDD sums. The results showed good alignment along with the three schemes. Therefore, the final decision was based on computation speed. Hence, in this PDD model, the semi-analytical approach proposed by Calov and Greve (2005) was applied simply due to its faster processing time and better accuracy for calculating PDD sums (Hallé, 2020).

The method developed by Carov and Greve (2005) employs a Normal (or Gaussian) distribution of the error function to predict the probability of temperature based on the monthly mean value. The PDD sum component is illustrated in *Equation 1*, where T_{ac} is the monthly temperature in

°C. The error function, *erfc*, is a built-in function in MATLAB and can be described as it is depicted in *Equation 2*.

Equation 1 - Positive Degree Day calculation

$$PDD = \int_0^A \left[\frac{\sigma}{\sqrt{2\pi}}\, exp\left(-\frac{T_{ac}^2}{2\sigma^2}\right) + \frac{T_{ac}}{2}\, erfc\left(\frac{T_{ac}}{\sqrt{2}\sigma}\right)\right] dt$$

Equation 2 - Error function (erfc) calculation

$$\mathrm{erfc}(x) = 1 - \mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} \exp(-x^{\sim 2})\, dx$$

The PDD sum computation requires the following input: air temperature data from the observational gridded seNorge climate dataset (see Section 3.1.1) and standard deviation. The standard deviation was calculated using observation-based temperature data derived from the closest weather station to each location.

3.5.2. Melt Model Component

Once the PDD sums are computed, the melt model component can perform snow and ice melt calculations over the glacier. Input for this particular element of the model is PDD sums calculated based on the method described in the previous subchapter, monthly near-surface air temperature (^{o}C) and precipitation (mm) from the seNorge and ERA5-Land climate datasets and geographic extent of each glacier and catchment in this study converted into binary images and used as masks to filter the results to the relevant areas.

Model parameters include the standard deviation of temperature, the threshold for reliable (snow) and liquid (rain) precipitation, and degree-day factors (mm/°C-1) for ice and snow, respectively. The standard deviation of air temperature (see Table 3) was calculated from the nearest weather stations for the summer season, including May, considering past research revealed that substantial melting takes place in May in Southern Norway (Engelhardt et al., 2014). Standard deviation was calculated for the period of 2016-2019. A sufficient amount of observations are available within this time-frame. The melt model applies a simple static threshold for distinguishing snow and rain from precipitation.

Every precipitation that falls when the temperature is below 0.5 °C will be accounted for as snow. The threshold value is based on the practices applied in the Norwegian version of the HBV model (Engeset, 2016) and personal communication with experts (Saloranta, 2020). The degree-day factor determines the amount of ice or snow that melts for every degree over the effective melt temperature (0 °C). Therefore, these factors have an immense influence on model performance, and ideally, it would have been obtained either through observations or calibration of the model by running a large volume of simulations and assessing the performance of the parameters simultaneously. Albeit not necessarily impossible, such a method exceeds the scope of this master thesis. Hence degree-day factors applied to the melt model in this study were adopted from prior research (Laumann and Reeh, 1993, Jóhannesson et al., 1995, Andreassen et al., 2006). Due to the scarcity of such previous research focusing on Bondhusbrea and Rembesdalskåka, compromises were made, and melt factors reported for the nearest locations were adopted for these two particular glaciers. Andreassen et al. (2006) reported best fit degree-day factors to simulate mass balance at Engabreen, whereas Laumant and Reeh (1993) and Jóhanesson et al. (1995) modeled mass balance at Nigardsbreen and their research revealed calibrated melt factors for snow and ice. Since Austdalsbreen is located in close proximity to Nigardsbreen, calibrated ice and snowmelt factors reported by Laumant and Reeh (1993) and Jóhanesson et al.

Table 3 - Standard deviation of temperature.

Location	WS	Std
Austdalsbreen	Bråtå-S.	2.7
Austdalsbreen	Grottlii	3.1
Austdalsbreen	Jostedalen	2.4
Bondhusbrea	Folg.-Ski.	2.3
Bondhusbrea	Skjeggedal	2.7
Engabreen	Engabreen-Skj.	3.1
Engabreen	Glomfjord	2.8
Engabreen	Glomfjord-Ski.	3.3
Rembesdalsk.	Finsevatn	3.3
Rembesdalsk.	Midstova	2.4
Rembesdalsk.	Fet	2.6
Rembesdalsk.	Skurdevikåi	3.1

(1995) were used for Austdalsbreen. Degree-day factors produced through mass balance model calibration in earlier studies are summarized in Table 4.

The model is programmed to loop through every month of the year over a given period. It begins by firstly arbitrating if the PDD sum in the given month is more than zero. Secondly, the model confirms if the surface is bare ground or snow or ice. If the model detects snow on the surface, it begins to melt it according to the predefined snowmelt factor. Once the snow is wholly depleted over the glacier surface, usually in the 7th month of the year, the model begins to melt the glacier ice using a typically higher melt factor than that used for snow, although it is known to vary both spatially and temporally (Engelhardt et al., 2014). The whole loop and process of calculating total melt from the PDD sum are presented in Figure 9.

Table 4 - Average degree-day factors for ice and snow as reported in earlier research.

Location	DDF_{ice} (mm w.e. $^{\circ}C^{-1}$ d^{-1})	DDF_{snow} (mm w.e. $^{\circ}C^{-1}$ d^{-1})	Period	Reference
Ålfotbreen	4.5	6.0	1961-1990	Laumann and Reeh (1993)
Hellstugubreen	3.5	5.5	1961-1990	Laumann and Reeh (1993)
Nigardsbreen	4.0	5.5	1961-1990	Laumann and Reeh (1993)
Engabreen	4.4	6.4	1964-1990	Jóhanesson et.al. (1995)
	3.8	5.9	2000-2004	Andreassen et.al. (2006)

The melt model was slightly altered in order to facilitate a more comprehensive assessment of model performance. Numerous outputs of the model run, such as snow accumulation on the glacier, glacier ice melt, snowmelt over the glacier, and snowmelt in the basin, were stored separately to assist the process of model validation and in-depth analysis of the contribution of glaciers to runoff.

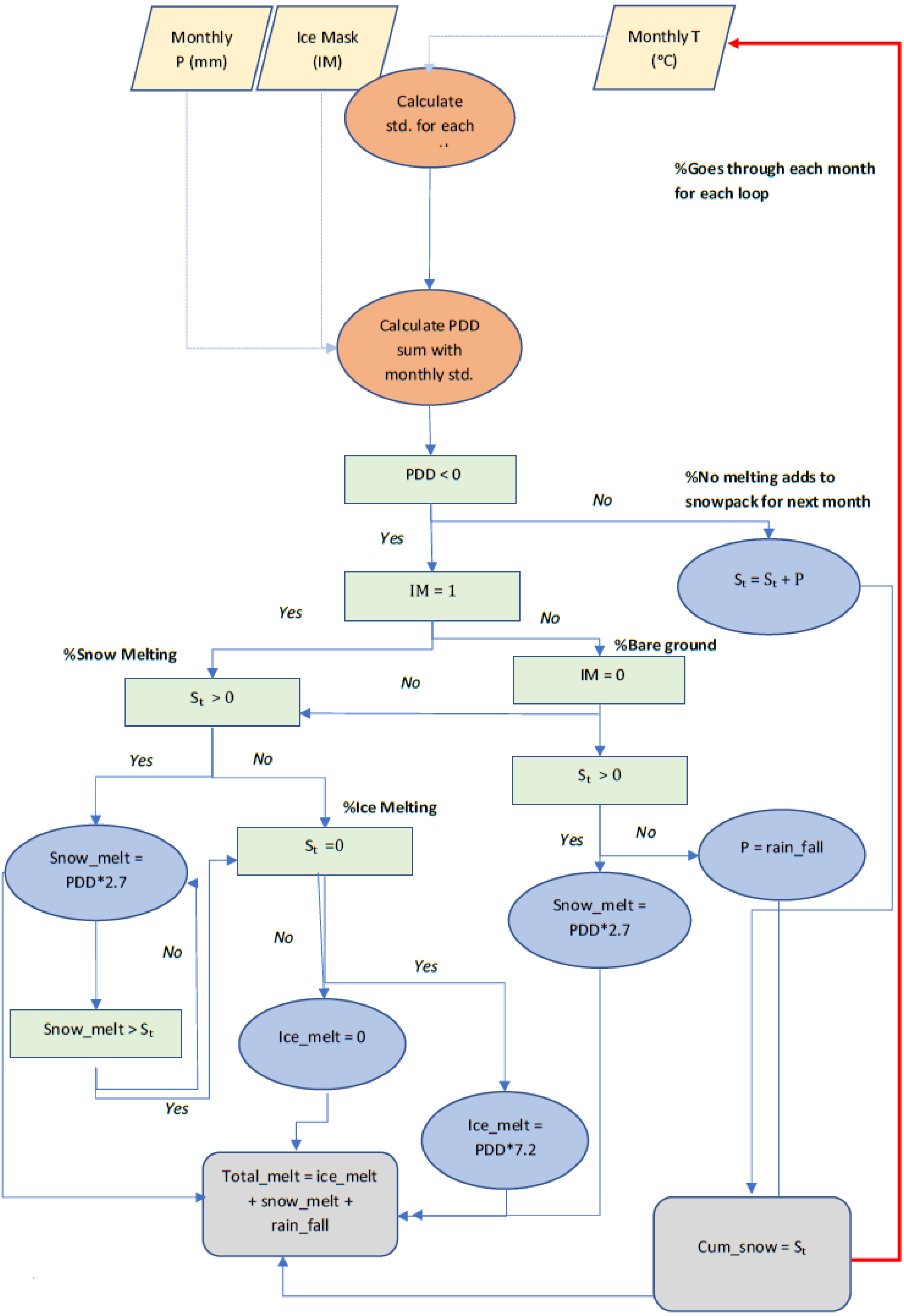


Figure 9 - Schematic representation of the PDD model process. Source: Hallé D.M., 2020

3.5.3. Validating the Performance of PDD Model

Assessing the performance of the model is essential to determine if it will accurately project future discharge in the study catchments. For this purpose, historical runoff observations and surface mass balance records were used, which were provided by the Norwegian Water and Energy Directorate (NVE).

Long-term annual mass balance measurements were available for three out of the four studied glaciers, with the only exception being Bondhusbrea in the South. The measurements are in the meter of water equivalent, and the dataset contains annual, summer, and winter balance. The equation to make the output of the PDD compatible with mass balance records is the following.

Equation 3 - Calculating monthly surface mass balance from run-off simulations

$$B_m = \frac{0.001[snowtotal_g - (snowmelt_g + icemelt_g)]}{\frac{area_g}{100}}$$

Where $area_g$ is the glacier extent in m^2, $snowtotal_g$ is total snow fallen on the in a given month, $snowmelt_g$ is total monthly snow melt, while $icemelt_g$ is the sum of monthly ice melt. These variables are in millimeter; hence the conversion to meter is necessary. The area of the glacier is divided by 100 because every grid cell is 100 m^2. The code first calculates the sum of every variable for the whole glacier area and then applies the equation. Calculating seasonal and annual surface balance requires to take the yearly maximum and minimum of monthly balances. MATLAB provides the perfect function for this purpose; therefore, the built-in retime function was used to take annual maximum and minimum values every year. Summer mass balance is obtained by subtracting the yearly minimum value from the maximum of the same year.

In comparison, winter balance is calculated by subtracting the maximum of the actual year from the previous year's minimum. The annual surface balance is then given as the sum of winter and summer balances. Finally, the modeled mass balance record is plotted against the mass balance measurements to determine the degree of agreement between simulated and measured surface mass balance.

Long-term runoff observations from gauging stations were available for two locations, Engabreen and Bondhusbrea; thus, providing an opportunity for an additional validation method. The streamflow records apply for the whole basin, or in the case of Engabreen, for the majority of the runoff catchment. First of all, the basins' total area was calculated by counting the number of grid cells in the catchment mask. After making sure that every cell account for 100 m2, the total area of the basin was calculated and converted to m2. Afterward, similarly to validating with mass balance measurements, monthly total discharge over the whole catchment was calculated by first taking the sum of all modeled runoff fields within the basin's boundaries and then dividing it with the area of the catchments. The observed discharge records comprise of daily average measurements in m3/second. Hence, to align it with modeled discharge, the following script was applied in MATLAB:

```
obs_runoff_mm = obs_runoff_monthly * 1000 * 24 * 3600 * days_in_month/
                          basin_area;
```

The observational data was first converted into monthly mean since the simulated discharge is in mm/month. The observed runoff can be converted into m/s by dividing it by the area of the basin. Following that step, the m/s values were transformed into mm/month by first multiplying it with 1000 to obtain mm/s, and then multiply it by the number of seconds in a month (24 * 3600 * days in a given month). Lastly, the simulated monthly discharge over the basin was plotted against the observed runoff records.

Once the PDD model simulated runoff was transformed into mass balance and discharge sums, two measures were calculated to quantify the effectiveness of the model, forced with the particular parameter set adopted from literature. Following the methods applied in earlier research by Engelhardt M. et al. (2014), the coefficient of variation (cv) was calculated to assess errors between measured and modeled mass balance, whereas the Nash-Sutcliffe coefficient for comparing monthly modeled discharge with observed values. The coefficient variation is a measure to evaluate the variability of, in this case, the standard deviation of the model generated and the measured mass balance records relative to the mean value at the chosen glaciers in the study. The coefficient of variation is determined through:

Equation 4 - Coefficient of variation calculation

$$c_v = \frac{\sigma}{|b_{meas}|} \quad \text{where}$$

$$\sigma = \sqrt{\frac{(b_{mod} - b_{meas})^2}{n}}$$

where *n* signifies the number of mass balance measurements. The Nash-Sutcliffe (NS) model performance coefficient was developed by Nash and Sutcliffe (1970) to evaluate the predictive accuracy of runoff models to simulate river flow (Nash and Sutcliffe, 1970) and most commonly used to assess the effectiveness of hydrological models. The perfect match between modeled and observed data is indicated by an NS value of 1.0. Nash-Sutcliffe coefficient can range between 1.0 to minus infinity, whereas NS below zero implies that the mean of the observed data is a better predictor than the modeled data. The Nash-Sutcliffe coefficient can be described by the following equation:

Equation 5 - Nash-Sutcliffe coefficient formula

$$NS = 1 - \frac{\sum(Q_o - Q_m)^2}{\sum\left(Q_o - \overline{Q_o}\right)^2}$$

in which Q_o denotes the total amount of monthly observed runoff.

3.6. Methods for Interviews

Norway is well-known for being a cold climate country on the edge of Northern Europe. However, Norway's geography with steep, rumbling rivers is perfect for providing the population and industry with sustainable and renewable energy in the form of hydropower. In fact, hydropower is responsible for 96% of Norway's total electricity production (Graabak et al., 2017). Besides, hydropower plant facilities, such as dams and tunnels, are often supporting efficient energy production and natural hazard mitigation. The primary purposes of such constructions are:

- Improve water-management by better controlling runoff and providing more extensive control over water resources for, among others, energy production
- Mitigate the consequences of potential natural disasters in the future. Hence, the thesis focuses solely on the threats glacier changes pose to hydropower and future energy supply.

How glaciers and hydropower intertwine? Mountain river catchments with considerable glacier cover are perfect locations for hydropower plants. In such circumstances, glacier meltwater may compensate for less precipitation in the summer season, and a significant portion of discharge may comprise melting glacier ice or accumulated snow over the glacier surface. Thus, in a world of ongoing climate change with ever-rising temperatures, the common assumption is that glaciers may significantly affect future hydropower development in several parts of the world. Is this the case in Norway? The introduction of qualitative methods and dialogue with hydropower and hydrology experts provides an additional tool to determine the extent to which fluctuations of highly glacierized catchments' runoff regimes may affect hydropower production in Norway's future. The interviews are designed to reveal information that could not be obtained from merely assessing runoff and climate drivers.

3.6.1. Semi-Structured Open-Ended Interviews

The proposed method by which this paper aims to shed light on the matter of potential consequences of shrinking glaciers on the hydropower industry is conducting a dialogue with hydrologists and hydropower production specialists in Norway. The most effective manner for such a dialogue is a semi-structured open-ended interview.

A semi-structured interview's main characteristic is that even though the interviewer leads the conversation by specific pre-defined questions, whereas the questions leave room for initially unaddressed subjects by being flexible (Dunn, 2016). Besides, due to the open-ended manner of the survey, follow-up questions may arise after interviews, which may result in obtaining additional vital information. Moreover, an open-ended questionnaire's prominent feature is that it does not promote strictly categorized answers and respondents are encouraged to extensively contemplate their answers (Farrell 2016).

3.6.2. Target Group

The study opted to conduct interviews with hydrology and hydropower experts who have massive experience and knowledge about the topic. Therefore, these interviews were a perfect fit for revealing experts' perceptions and information not possible to determine by merely analyzing the available data and the results of the PDD model. Statkraft, the most prominent Norwegian energy provider with a significant interest in hydropower production, appeared to be one of the obvious choices for such interviews.

The Norwegian Water and Energy Directorate is responsible for managing the water resources and ensuring efficient energy production. Moreover, NVE has a significant hydrology and glacier research department. The institute is engaged in numerous research projects focusing on climate change induced changes in glaciers and hydrology, proving to be another apparent choice for interviews. However, NVE publishes both results of ongoing research and data, which are therefore freely available for everyone. Whereas Statkraft is a direct actor in the hydropower market, therefore the company's policy for sharing internal information is significantly more exclusive and stricter. Moreover, NVE experts contributed to this study tremendously by providing data and advice, and research conducted at NVE is already firmly incorporated into this study.

Ideally, experts from every region in the focus of this study would have been interviewed. Nevertheless, not every person who was contacted agreed to participate. Eventually, three hydrology experts were interviewed. Even Loe, who is a hydrologist at Statkraft, working specifically in the highly glacierized Jostedalsbreen region. Gaute Lappegard, Head of Hydrology at Statkraft, previously researcher at NVE. Las but not least, Sigrid Bojesen Fatnes, a hydrologist at Statkraft in the South-West Norway region.

3.6.3. Arrangement of Interviews

After consideration, the interviews were distributed electronically in a written form (Word document), and answers were collected through email. The primary intention was to involve experts from every selected study location, therefore, interviewing experts personally would have been a time and money-consuming process (McGuirk and O'Neill, 2016). In addition, interviewing people in person in a foreign language may lead to biases and limited answers due to unnecessary stress. Therefore, the written survey was an ideal option to allow respondents time in a comfortable environment. In addition, the collection of answers in a written form increased time efficiency by requiring less time for processing the answers.

On the other hand, communication in written form carries limitations, such as the complete absence of personal reactions to certain questions, and the possibility of determining the level of engagement or concern specific questions may trigger. Besides, misunderstanding may emerge more frequently when communicating in written form (McGuirk and O'Neill, 2016). However, the issue of misunderstanding can be mitigated with clearly formulated questions and follow-up messages. Throughout this study, no major misunderstanding arose.

3.6.4. Final Questions in the Survey

The interviews involved the following questions.

I. What are the biggest challenges in general regarding the possible effects of reducing glacier meltwater on hydropower production in Norway? How could it affect future hydropower development?

II. Do Statkraft consider these potential challenges while working out strategies for future (long-term) hydropower development? If yes, how is it included in planning?

III. Is there ongoing research regarding the topic in Norway? What steps Statkraft make to learn more and be more aware of the exact extent of the potential impacts of climate change triggered glacier retreat?

IV. Do Statkraft co-operate with scientific institutions to better measure and comprehend the impacts of glaciers in the future?

This study's main objective is to gather and interpret the perceptions of hydropower experts on the future of hydropower development in glacierized regions of Norway and couple it with findings of the runoff model to answer the research questions. The first question addresses this issue directly. Secondly, to understand and estimate the potential impacts of glaciers on the hydropower industry, it is vital to apprehend the hydropower industry's adaptation to climate change. The second question of the questionnaire intends to shed light on this issue.

Further questions emerged following the previous two. How are significant future risks being assessed? Furthermore, how organized is the research regarding the subject in Norway? Do different institutions cooperate in evaluating future runoff scenarios and consequent effects in the industry in Norway? Question III. and IV. address these points.

3.6.5. Processing of Responses

Following the interviews, answers were collected and stored until the thesis was submitted to comply with requirements established by the Norwegian Center for Research Data (NSD). An official request was submitted to NSD in the early stages of the study for obtaining permission to collect personal data for research purposes. Following revisions and discussion, the decision was made to involve the names of the experts who participated in the surveys in order to emphasize the creditability of the answers. All respondents agreed to include their names.

The responses were lightly processed and categorized according to the survey questions. Afterward, the answers were interpreted and presented in a straightforward manner by merging responses of the experts to answer each question comprehensively. The results of the interviews are presented in Section 4.5.

4. Results

4.1. Exposing Climate Trends in Norway

Aiming at comprehending the drivers of glacier behavior as thoroughly as possible, this study carries out an analysis of climate variability of the last 60 years to accentuate regional diversity of temperature and precipitation regimes within the boundaries of Norway. The basis of the climate trend evaluation is the seNorge climate dataset (see Section 3.1.1.).

In terms of temperature and precipitation, the four chosen study regions represent two fairly distinct types of climates. Whereas mean annual temperature at Engabreen and Bondhusbrea are firmly close to or above 0 ^{o}C, Austdalsbreen and Rembesdalskåka, which are located at higher elevations and further away from the coast, are exposed to colder climate conditions with the average annual temperature rarely above 0 ^{o}C. Precipitation is typically higher in the proximity of the coast and on the west-facing slopes of the Scandinavian Mountains, whereas it decreases with increasing climate continentality. Among the selected study sites, Bondhusbrea receives the highest precipitation, followed by Engabreen. The case of these two glaciers is an excellent example of a more considerable influence on precipitation regimes by the distance from the coast than latitude. At Austdalsbreen and Rembesdalskåka, precipitation rates are lower compared to the other two areas, mainly due to firmer continental settings. In particular, winter precipitation is essential for glaciers since it determines the degree of accumulation during winter and heavily influences summer runoff regimes.

4.1.1. Variability and Trends in Near-Surface Air Temperatures

Summer and winter temperatures vary greatly both spatially and temporally in the four areas of interest (see Figure 10). A noticeable and steady general rise of temperature can be observed at every site throughout the examined period. When investigating temporal changes in temperature during the last 60 years, which involves the aforementioned interval characterized by colder climate conditions, a substantial increase can be observed in winter and, most importantly, in summer temperatures at every location. The latter, however, carries more prominent importance for studies focusing on quantifying glacier meltwater runoff. Since winter temperature is of less significance, it will not be discussed here in detail. At Austdalsbreen, in 1979-1999, the average summer temperature was 3.47 ^{o}C, whereas it climbed to 4.58 ^{o}C in the course of the last 20-year period (1999-2019), signaling a pronounced warming trend with an increase of over 1 ^{o}C. At Bondhusbrea, summer temperature varied between 3.58 ^{o}C (1959-1979), 3.92 ^{o}C (1979-1999), and 5.01 ^{o}C (1999-2019), therefore, also showing a steady summer temperature rise throughout the last 60 years. This trend continues to emerge at Rembesdalskåka as well. In the interval of 1959-1999, the mean summer temperature oscillated around 4.03 ^{o}C, while showing a slight decrease in temperature in the second half of this period. However, during the succeeding 20 years, an increase of 1 ^{o}C occurred, resulting in a mean summer temperature of 5.03 ^{o}C. In the north, at Engabreen, summer temperatures averaged 5.44 ^{o}C between 1959 and 1979. The following twenty years brought a modest increase (5.81 °C), culminating at 6.81 °C during the last interval, spanning from 1999-2019.

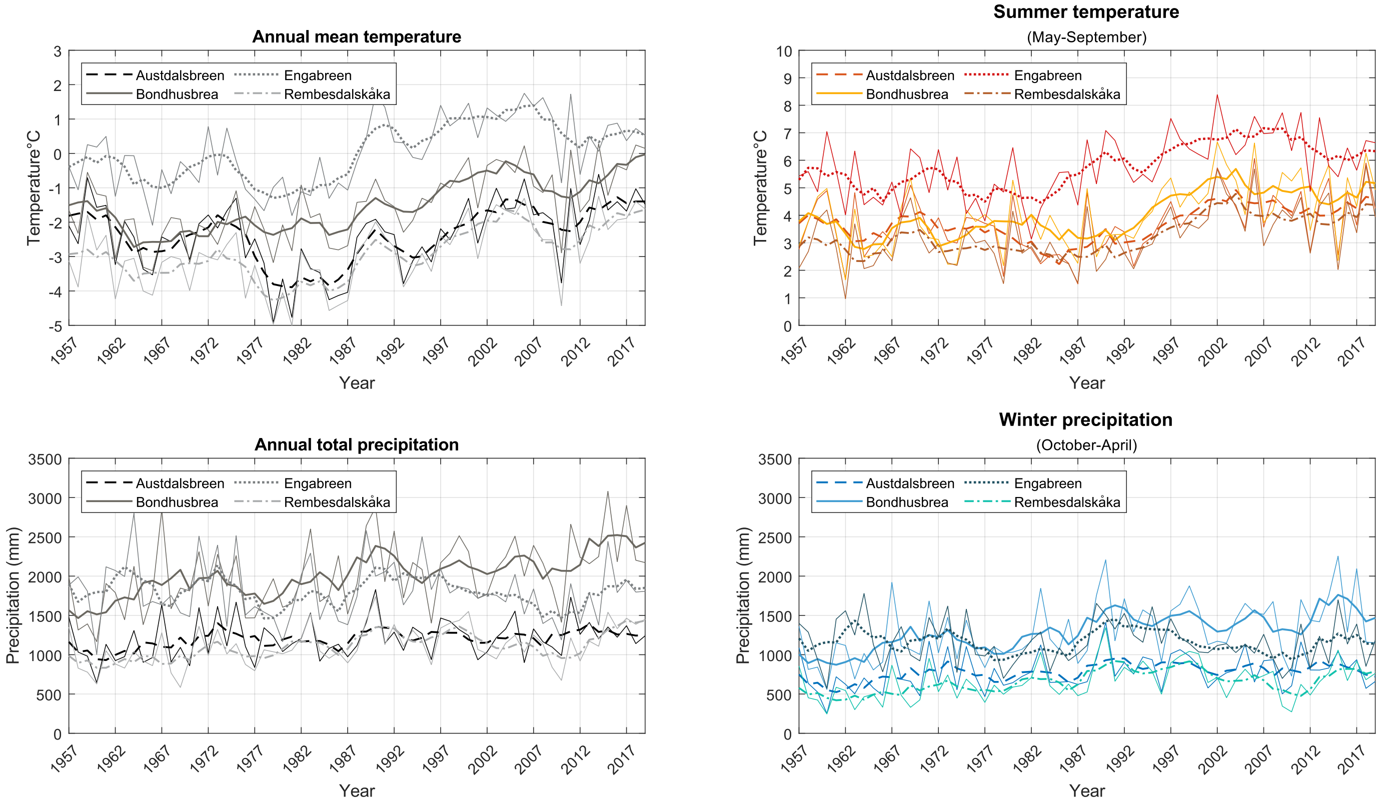


Figure 10 - Reconstructed seasonal and annual mean temperature and total precipitation between 1957 and 2019 in the ablation zone of the four glaciers included in this study. Source of climate data: seNorge

Spatially, there are considerable fluctuations from region to region. In the southernmost location, at Bondhusbrea, summer temperatures varied within the range of 1.72 °C – 7.10 °C and averaged at 4.17 °C in the last 60 years. At Rembesdalskåka, which is characterized by the most continental climate among the selected study areas, the same range is 2.11 °C – 7.25 °C, and the mean summer temperature for the last sixty-year timeframe is 4.36 °C. When moving to the north-east, at Austdalsbreen, climate data analysis revealed that mean summer temperatures oscillated within the range of 1.90 °C and 6.85 °C (4.03 °C on average), which is considerably lower than observed at the previous two locations. This is an expected anomaly for a glacier with a generally high average altitude and semi-continental climate regimes. Reaching the northernmost location in this study, at Engabreen, investigation of historical seNorge temperature data unveiled notably high mean summer temperatures in fluctuating within the range of 3.29 °C – 9.07 °C around an average of 6.01 °C. This phenomenon can be explained by the geographic settings of the examined glacier area, which, in the case of Engabreen, starts at considerably lower elevations in a valley in the proximity of the ocean.

4.1.2. Variability and Trends in Precipitation Regimes

Winter precipitation carries an immense impact on annual discharge in highly glaciated basins. Therefore, this subchapter will focus on the spatial and temporal variation in precipitation. Furthermore, a simple snow/rain fraction analysis will shed light on the fraction of solid and liquid precipitation in the selected regions of Norway.

In terms of temporal diversity, a general increase in total annual winter precipitation can be observed throughout the investigation period (1959-2019) in every area involved in this study. Nevertheless, at Engabreen and Rembesdalsåka, winter precipitation receded from the twenty-year period of 1979-1999 to 1999-2019 by circa 5%. Located on the west side of the Hardangerjökull icecap, Rembesdalskåka witnessed a less significant increase in winter precipitation throughout 1959-1999, followed by a decrease in most recent times. Based on the seNorge observational dataset, the annual total winter precipitation at Rembesdalskåka varied insignificantly, between 941 mm (1959-1979), 966 mm (1979-1999), 922 mm (1999-2019). The ratio of snow and rain in the same interval changed from approximately 2.7% to 8.1%. In the maritime environment, at Engabreen, the analysis revealed a similar trend to that identified at Rembesdalskåka. Winter precipitation averaged at 921 mm during 1959-1979, which followed a relatively sharp increase in total mean winter precipitation with 955 mm (1979-1999). Finally, an ample decrease occurred in the last two decades (1999-2019), leading to a mere 908 mm average winter precipitation. The ratio of solid winter precipitation is considerably higher here, at Engabreen than in any other study area, with a range of 11.4% in 1959-1979, followed by an enormous increase to 26.4%. At Bondhusbrea, which is the glacier with the highest precipitation out of the four studied glaciers, observations show a steady increase in winter precipitation from 874 mm during the first two decades to 1144 mm during the subsequent two decades and finally to 1216 mm during the last two decades. At the same time, the ratio of solid and liquid winter precipitation varied from 3.4% to 9.6%. At Austdalsbreen, under more continental settings, and on the east slopes of a natural topographic barrier, a more arid climate occurs. Consequently, annual precipitation, as well as its winter counterpart, are substantially lower at Austdalsbreen compared to the previously discussed locations. During the first twenty-year long time frame (1959-1979), annual total precipitation averaged at only 563 mm. Nonetheless, the following decades brought a significant increase in precipitation resulting in 693 mm (1979-1999) and 695 mm (1999-2019), while the proportion of solid and liquid precipitation barely increased from 2.9% to 3.3%.

4.2. Results of Regional Climate Model Assessment

One of the main objectives of this study is to enable future runoff projections for the selected catchments in Norway. In order to fulfill this aim, an assessment of regional climate models (RCM) is essential. Following a review of prior research on model prediction skills across Norway and personal communication with experts, the RCA4 regional climate model (see Section 3.1.3.) with an 11 km spatial was selected to simulate future discharge in glacierized basins. In this chapter, outputs from original and three bias-adjusted model datasets (see Section 3.1.3.) are evaluated against observational data from weather stations. The reference period of 1979-2019 for model prediction skill assessment differs from the time range of climate data analysis since RCM historic output was only available from 1979, whereas seNorge climate variable records are created from 1957. In addition, the performance of the state-of-the-art climate reanalysis ERA5-Land and the national observational climate dataset, seNorge, is also evaluated as potential reference data for region-wide assessments. Since both ERA5-Land and seNorge are, to a varying degree, observational data products, these datasets presumably perform better than observation-independent regional models. Figures in this section only show an assessment of temperature due to the large sums of errors were found in the numerical analysis of climate model-generated precipitation. However, the overall evaluation of model performance – precipitation included – is presented in Table 5 and Table 6.

Weather stations covering the entire reference period are scarce. Henceforth, data from most weather stations only cover certain portions of the reference period. Keeping in mind these limitations, the complete time-frame of the historic RCM simulations was evaluated using the entire available set of weather station measurements. The study applied a root mean square error (RMSE) statistical test (see Section 3.3) to evaluate the performance of differing climate data assortments. A summary of the weather stations utilized in this part of the study is presented in Table 3.

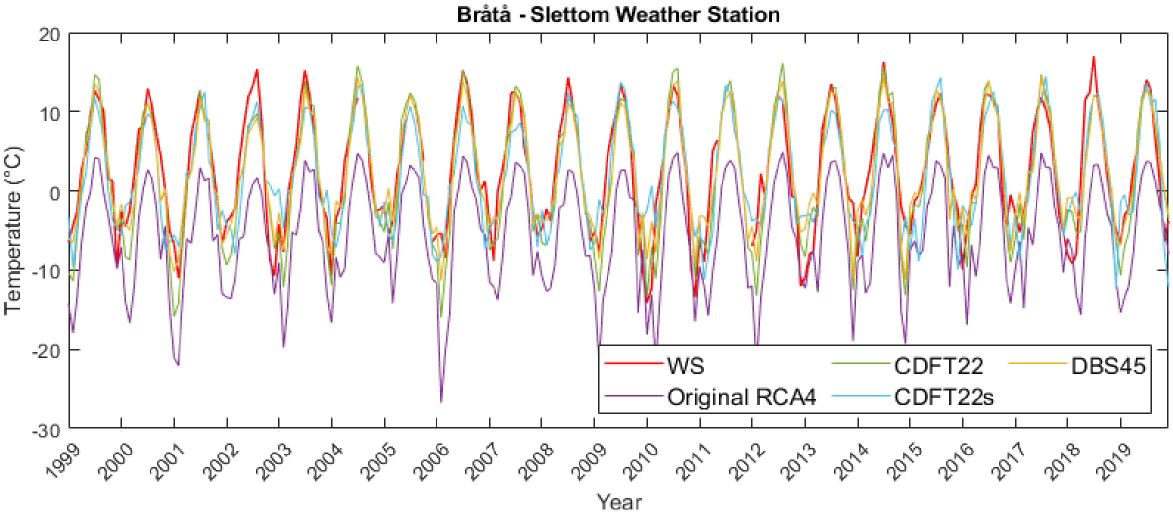
Austdalsbreen

In the proximity of Austdalsbreen, two weather stations were considered suitable for evaluating the model performance. Bråtå-Slettom (664 m.a.s.l.) station provided both near-surface air temperature and precipitation observations for 1999-2019, whereas data for 1984-2003 was retrieved from the Bjørkehaug (305 m.a.s.l.) weather station (WS). At Bråtå-Slettom, the mean monthly temperature varies in the range of -14,1 ^{o}C - +17 ^{o}C throughout the year, while Bjørkehaug WS indicates a temperature range of -11,3 ^{o}C to +16 ^{o}C. The average monthly total precipitation is 118 mm at Bjørkehaug and 47 mm at Bråtå-Slettom. Both weather stations are located in a complex topographic environment surrounded by steep mountain slopes.

The evaluation of seNorge and ERA5-Land reference climate datasets were performed the same way as for the RCM and its bias-corrected versions. The results revealed that due to its nature as observational dataset, seNorge vastly outperformed both ERA5-Land and RCm versions with respect to both temperature and precipitation at the two weather stations near Austdalsbreen. However, ERA5-Land demonstrated poorer skill for simulating temperature than the bias-adjusted RCM versions. Concerning precipitation, ERA5-Land performed considerably better compared to the RCM versions and the deviation from seNorge was smaller than for temperature at both Bråtå-Slettom WS and Bjørkehaug WS. RMSE for ERA5-Land and seNorge are presented in Table 5 and Table 6, providing a reference for evaluating RCM performance.

As presented in Figure 11 and in Table 5, the original RCA4 outputs produced higher RMSE values and performed worse in simulating temperature at Bråtå-Slettom compared to performance at the other weather station. The statistical test of the original RCA4 model outputs (Section 3.3) resulted in an RMSE of 9.25 ^{o}C at Bråtå-Slettom and 10.76 ^{o}C at the Bjørkehaug WS. Bias-adjusted climate model products followed a similar pattern; however, all bias-corrected versions significantly outperformed the original RCA4 model in this region both for temperature and precipitation (see Table 5 and 6). The DBS45 bias-correction method produced the lowest RMSE values of 3.2C and 3.51C at both weather station locations, respectively, which signals considerable improvement compared to the errors produced by the original RCA4 regional climate model simulation.

Regarding precipitation, as it has already been demonstrated for ERA5-Land by the findings of the limited analysis in this study, global climate products seem to struggle to capture the observed precipitation patterns, particularly in regions with complex terrain such as Norway's landscape. The original RCA4 simulations resulted in an RMSE of 77.21 mm (Bråtå-S) and 261.29 mm (Bjørkehaug). Similarly to temperature, adjustments by statistical methods improved model performance substantially. The lowest RMSE values at Bråtå-Slettom WS occurred for the CDFT22 bias-adjusted output (Section 3.1.3.3) with a value of 38.96 mm, whereas the statistical test revealed that the DBS45 bias-correction method (Section 3.1.3.3) performed best at a slightly more complex environment at the Bjørkehaug WS generating an RMSE of 99.71 mm. Assessment of the original and all bias-corrected model outputs with corresponding RMSE values are summarized in Table 5 for temperature and in Table 6 for precipitation.



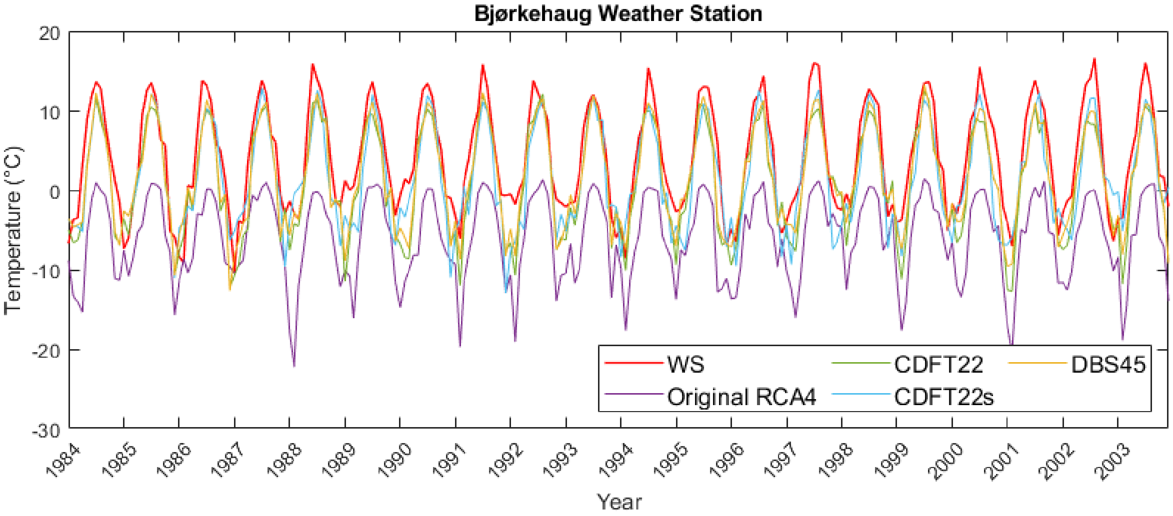


Figure 11- Temperature data obtained from weather stations plotted with various versions of RCA4 regional climate model at two weather station locations in the proximity of Austdalsbreen.

Bondhusbrea

The Bondhusbrea region includes three weather stations at various locations around the Hardanger-fjord. The availability of long-term temperature and precipitation observations from nearby weather stations is low; hence the involvement of farther located stations, such as the Omastrand WS, was unavoidable. Two WS provided temperature observations, and two WS served as validation of precipitation. Both climate variables are measured at the Omastrand WS (2 m.a.s.l.). Monthly average temperatures at Omastrand WS varied between -3.2 ^{o}C and +18.1 ^{o}C in the period of 1979-2001. Average monthly precipitation in the same interval was 220.2 mm. Temperature observations for a relatively short extent of time (2016-2019) were also available from the Folgefonna Skisenter WS (1212 m.a.s.l.) with a max temperature of 10.6 ^{o}C and a minimum of -7.6 ^{o}C. Lastly, precipitation observations were obtained from the gauging station in the town of Rosendal (75 m.a.s.l.) for the whole reference period (1979-2019) with a mean monthly precipitation of 163.4 mm.

The assessment of climate data products revealed that seNorge is consistently performing exceptionally well for temperature and outperformed other datasets at both WS in this region. ERA5-Land, on the other hand, showed significant variations in capturing temperature. It outperformed every version of the RCM at the higher altitude WS (Folgefonna Skisenter), while it implied worse skills at Omastrand, which lies at a significantly lower elevation. This tendency was later confirmed when assessing the improvements implemented by downscaling ERA5-Land (see Section 4.3.2.). The downscaling resulted in the most extensive improvements at low and middle elevation locations. Concerning precipitation, seNorge performed best, particularly at the Rosendal WS, while it outperformed other data products to a smaller degree at Omastrand WS. ERA5-Land demonstrated similar skills for capturing precipitation at both WS with smaller RMSE than all RCM versions suggesting better capabilities to simulate precipitation regimes in this environment. Evaluation of ERA5-Land and seNorge is also presented in Table 5 and Table 6, providing a reference for examining RCM performance.

The original climate model performed significantly better in this region compared to other locations. In contrast to RMSE values close to 10 ^{o}C in the proximity of Austdalsbreen, the original RCA4 model run generated considerably lower errors in the broad region of Bondhusbrea. The assessment resulted in an RMSE of 4.85 ^{o}C at the Omastrand WS, whereas the statistical test revealed a RMSE of only 3.13 ^{o}C at the Folgefonna Skisenter WS. The Folgefonna Skisenter WS was the sole location where the original model outperformed the bias-corrected versions (see Table 5), which is apparent from Figure 12. At the Omastrand WS, the

DBS45 bias-correction method performed best, producing a measure of the difference of 2.16 ºC. Every version – both original and bias-corrected - of the RCA4 model captures seasonal variations well, however visibly underestimating winter minimum temperatures (see Figure 12).

The regional climate model (RCM) and its modified versions failed to capture precipitation adequately in this region too. The original model output resulted in an RMSE of 183,65 mm (Rosendal WS) and 223,05 mm (Omastrand WS), respectively. In contrast, the modified version of the model, which is based on the CDFT22 adjustment method, produced RMSE of 180,1 mm (Rosendal WS) and 139.15 mm (Omastrand WS); thus, demonstrating the highest accuracy for replicating observations (see Table 6). An overall summary of model performance is presented in Table 5 for temperature and in Table 6 for precipitation.

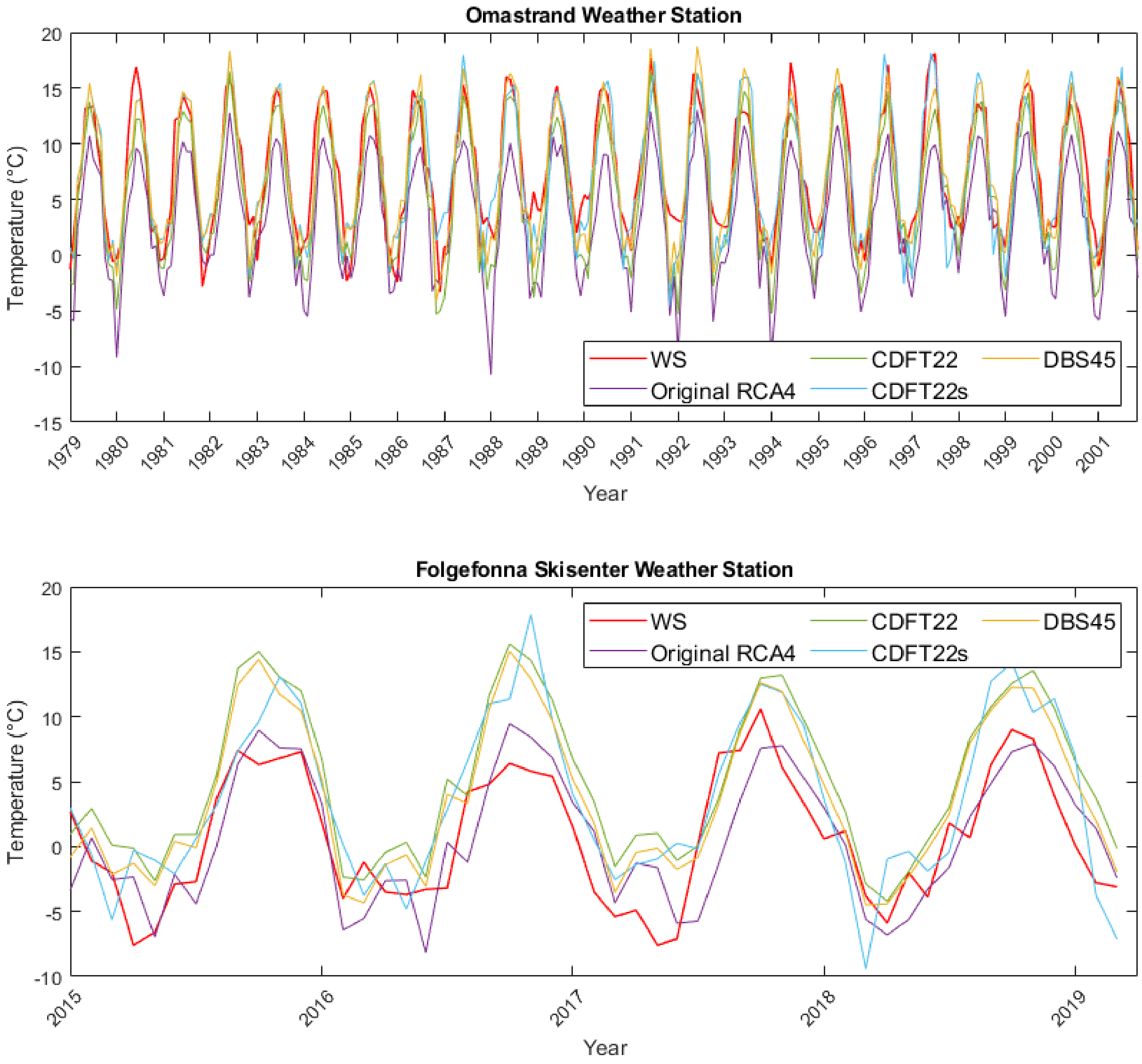


Figure 12 – Temperature data obtained from weather stations plotted with various versions of RCA4 regional climate model at two weather station locations in the proximity of Bondhusbrea.

Engabreen

The examination of climate model efficiency in the northernmost location in the study, at Engabreen, was facilitated with observational data from two weather stations. The Glomfjord weather station (WS) (39 m.a.s.l.) provided temperature observations for the entire reference period of 1979-2019 and precipitation records for 1979-2002. In addition, both temperature and precipitation data were collected from Glomfjord Skihytta (520 m.a.s.l) WS for the interval of 2015-2016. Mean monthly temperature range varied between -4.8 ^{o}C and +18.1 ^{o}C at the Glomfjord WS which is located at lower altitude, whereas the temperature ranged between -5.6 ^{o}C and 13.9 ^{o}C at. Precipitation averaged at 177.4 mm at the first station, whilst 155.8 mm at the second WS.

At the two WS in the proximity of Engabreen, seNorge demonstrated the best skills to capture both temperature and precipitation. However, the generated one of the highest RMSE for the lower altitude Glomfjord WS out of all involved WS. This might be due to the complex topographic settings with swiftly changing terrain even within the high resolution 1 km^2 grid cells of seNorge. ERA5-Land produced a similar RMSE pattern with lower RMSE at the higher elevation WS (Glomfjord Skihytta). Overall, ERA5-Land performed better for temperature and precipitation than the original RCM output; however, the bias-corrected versions demonstrated better skills for simulating temperature, but not for precipitation. Error estimates corresponding to every climate data product, including ERA5-Land and seNorge, are comprehensively presented in Table 5 and Table 6.

In general, the climate model successfully reproduces seasonal temperature cycles with a more realistic performance for summer maximum temperatures. Considering the objective of the study, summer – the melting season – is of greater concern. Every assessed version of the RCA4 model regularly predict lower winter temperatures than observed at weather stations. As presented in Figure 13, bias-correction techniques produced the most prominent improvement in summer temperature whilst generally leading to an enhanced model performance. This phenomenon occurs at every location an assessment of the RCM performance was performed. Similarly to previous study sites, the statistical analysis of the DBS45 correction produced the lower error with RMSE of 4.93 ^{o}C (Glomfjord WS) and 2.62 ^{o}C (Glomfjord Skihytta). For comparison, RMSE values of the original regional model are 7.45 ^{o}C and 4.08 ^{o}C; hence indicating major improvements by implementing bias-corrections (see Figure 13 and Table 5).

The statistical RMSE test suggests a similar model performance at Engabreen to that reported at Bondhusbrea. Despite the fact that bias-adjusted model versions slightly outperformed the original model output, the statistical test has revealed unusually small differences. In a similar manner to previously presented study sites, the CDFT22 bias-corrected model version shows the highest degree of success in capturing local precipitation regimes (see Table 6). Pertinent RMSE measures are 150.20 mm at Glomfjord WS and 168.99 at Glomfjord Skihytta WS, whereas the original RCM has generated RMSE of 172.97 mm and 175.85 mm.

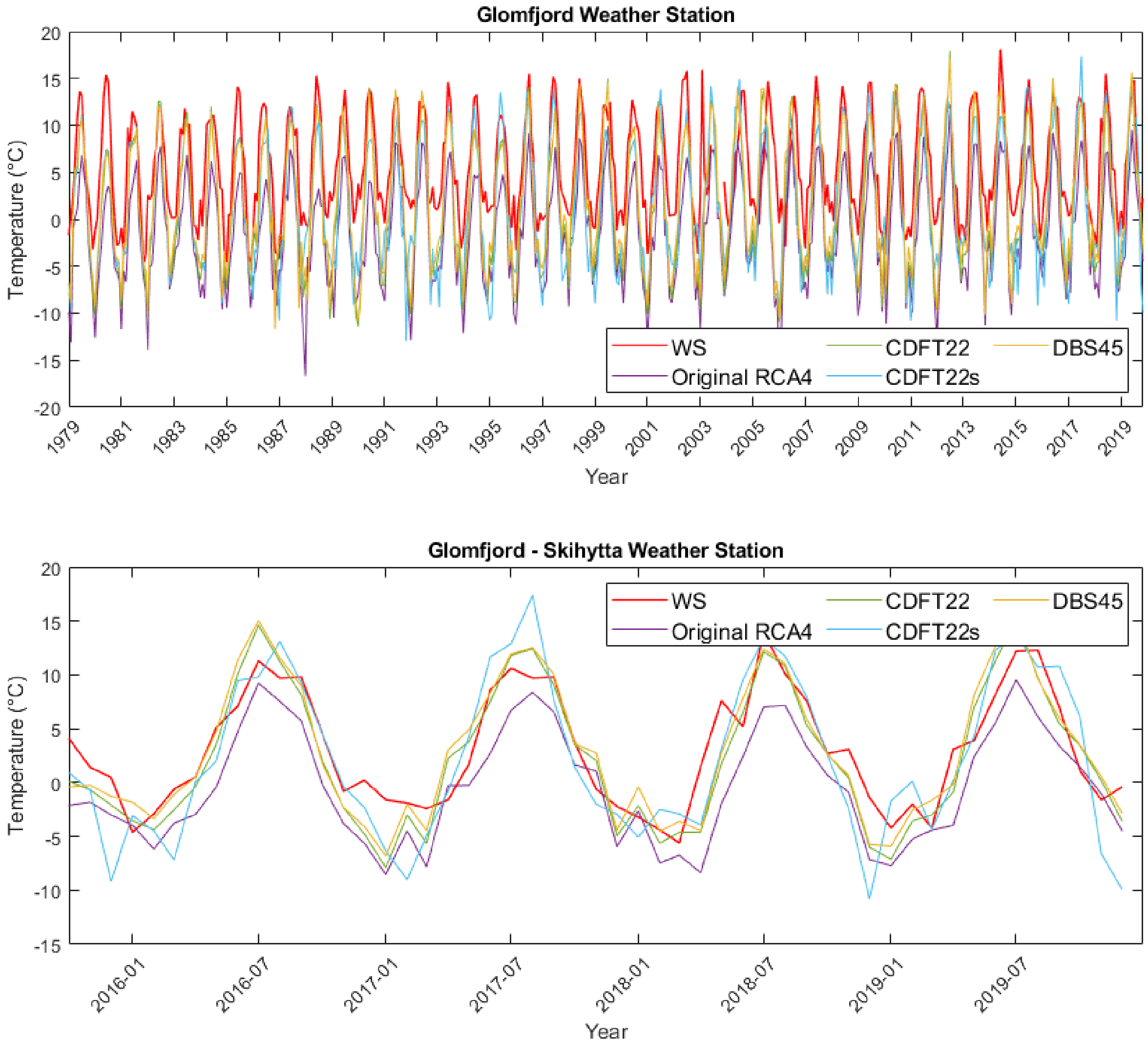


Figure 13 - Temperature data obtained from weather stations plotted with various versions of RCA4 regional climate model at two weather station locations in the proximity of Engabreen.

Rembesdalskåka

Four weather stations provided basis for analysing regional climate model performance in the proximity of the Rembesdalskåka glacier. Two weather stations at Finse and Finsevatnet are close to each other but together cover almost the complete reference period (1979-2019). Temperature observations were collected from Finsevatnet WS (1223 m.a.s.l.) for 1979-1990, from Finse WS (1210 m.a.s.l.) between 2006 and 2019 and lastly from the Midstova weather station (1162 m.a.s.l.) for a shorter period of 2016-2019. Mean monthly temperature varied between -16.3 °C and 12.6 °C at the Finsevatnet WS, -17.1 °C and 9.6 °C at Finse weather station whilst it moved in the range of -10.3 °C and 13 °C at Midstova WS. The weather station at Finsevatnet lacked consistent precipiation data; thus it was replaced with Liset WS (748 m.a.s.l.) in the analysis of the regional model outputs. Monthly precipitation at Finse WS was 92.4 mm, 100.5 mm at Liset WS and 127.75 at the Midstova weather station.

ERA5-Land demonstrated the best skill for capturing both temperature and precipitation in the vicinity of Rembesdalskåka. Despite the better performance showed by seNorge when it comes to temperature, ERA5-Land generated considerably lower RMSE at the three WS in this region than in any of the three other regions, suggesting a tendency of increasing performance with decreasing complecity of the geographic settings. Concerning precipitation, ERA5-Land outperformed seNorge at two out of the total three WS in the region. The evaluation of ERA5-Land and seNorge is summarized in Table 5 and Table 6.

The various versions of the RCA4 RCM effectively captured seasonal trends in temperature. However, the original version of the model regularly underestimated summer temperature considerably. The bias-correction methods substantially improved this short-coming and performed well in this region, which is supported by the RMSE generated by the statistical test (see Table 5). The consistently low RMSE values are probably the results of the less complex and heterogenous terrain in the surroundings of the weather stations on the plateau of Hardangervidda. Model version DBS45 outperformed the other versions of the regional climate model at two out of the three weather stations for temperature (see Figure 14 and Table 5).

The climate model has also captured the the observed precipitation patterns relatively well compared to other study sites. The most probable reason for this lies in the previously discussed topographic conditions in the vicinity of Rembesdalskåka and weather stations. Contrary to earlier good results of the CDFT22 bias-correction method, this time the CDFT22s version generated the lowest RMSE values for precipitation (see Table 6).

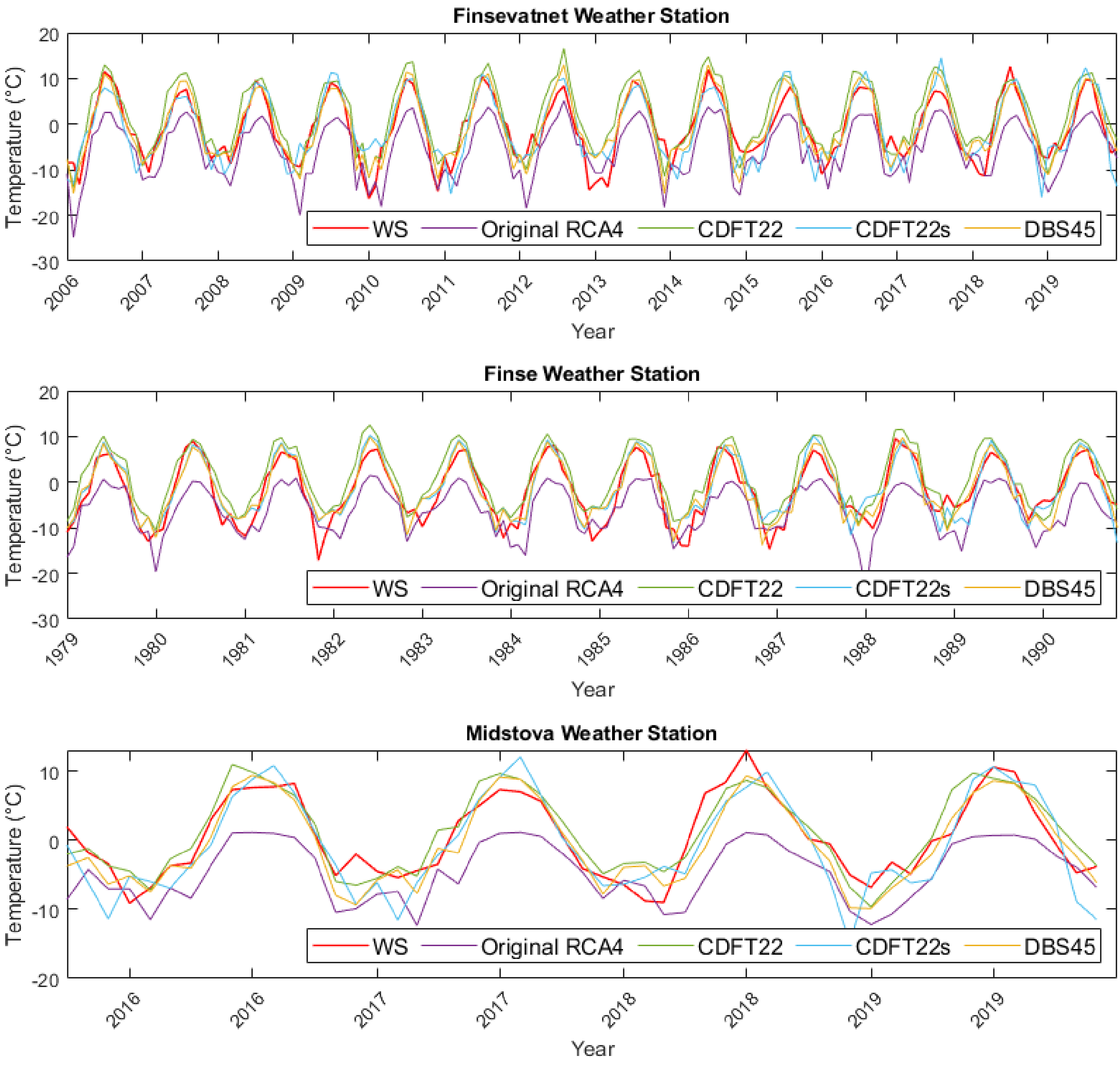


Figure 14 - Temperature data obtained from weather stations plotted with various versions of RCA4 regional climate model at two weather station locations in the proximity of Rembesdalskåka.

Conclusion of model assessment

The results of the statistical test shed light on the performance of the RCA4 regional climate model and its bias-corrected versions. Bias-adjustment methods significantly improved model skill in general and the modified versions of the model generated considerably lower RMSE values supporting this statement. When comparing regional climate models to reference datasets, most bias-corrected versions of the climate model outperformed the ERA5-Land climate reanalysis with respect to temperature. However, due to its nature, the Norwegian observational climate dataset, seNorge mirrors observations impressively and substantially outperforms other analyzed products (see Table 5). Since seNorge is based on observational data from several hundreds of weather stations throughout Norway, this outcome was expected.

On the other hand, all evaluated climate datasets have limitations when it comes to precipitation (Table 6). The large differences between modeled and observed precipitation might be exaggerated due to a known bias in precipitation gauging stations in Norway caused by under-catch of precipitation in windy conditions (Wolff et al., 2015).

With respect to temperature, the DBS45 model version outperformed other model versions at seven out of nine weather station locations. Conversely, this same method has not demonstrated the same impressive skill for precipitation. Precipitation observations were captured most realistically by the model output corrected by the CDFT22 method. In conclusion, results of RCM assessment suggest that applying a specific bias-adjustment method may not improve both precipitation and temperature to the same extent. Nevertheless, the evaluation carries uncertainties, such as limited numbers of WS and the use of only one statistical test; thus, needed to be interpreted accordingly.

Based on the RMSE statistical analysis, temperature from the DBS45 version and precipitation from the CDFT22 version of the RCA4 regional climate model were selected to be downscaled and used for generating future runoff projections as temperature and precipitation input.

Table 5 - Root mean square error (RMSE) values representing the difference between modeled and observed temperature in ºC.

WS	Period	CDFT22	CDFT22s	DBS45	Original RCA4	ERA5-Land	seNorge
Bråtå-Slettom	1999 -2019	3,61	3,89	3,20	9,25	4,40	0,77
Bjørkehaug	1984-2003	4,03	3,87	3,51	10,76	6,97	0,34
Omastrand	1979-2001	2,85	2,43	2,16	4,85	4,00	0,52
Folgefonna S.S.	2016-2019	5,10	4,45	4,23	3,13	2,24	0,42
Glomfjord	1979-2019	5,32	5,35	4,93	7,45	6,96	2,76
Glomfjord S.H.	2015-2019	2,62	3,96	2,62	4,08	3,77	0,79
Finse	1979-1990	3,98	3,54	3,06	5,79	1,58	0,52
Finsevatnet	2006-2019	3,96	3,11	2,96	5,54	1,37	0,45
Midstova	2012-2019	2,94	3,44	3,03	5,81	1,95	0,58

Table 6 - Root mean square error (RMSE) values representing the difference between modeled and observed precipitation in millimeter.

WS	Period	CDFT22	CDFT22s	DBS45	Original RCA4	ERA5-Land	seNorge
Bråtå-Slettom	1999 -2019	38,96	43,55	52,09	77,21	65,24	18,81
Bjørkehaug	1984-2003	127,51	100,31	99,71	261,29	55,25	21,04
Rosendal	1979-2019	180,10	192,31	198,93	183,65	85,75	13,54
Omastrand	1979-2002	139,15	163,93	187,36	223,05	85,76	62,10
Glomfjord	1979-2019	150,20	155,01	159,77	172,97	47,73	30,55
Glomfjord S.H.	2015-2019	168,99	169,85	169,41	175,85	52,43	40,14
Finse	1979-1990	115,91	101,82	106,28	157,10	35,27	22,04
Liset	1979-2010	82,14	84,44	88,09	184,94	36,43	43,24
Midstova	2012-2019	131,63	115,23	149,17	295,67	52,32	81,82

4.3. Results of Downscaling

4.3.1. Slope Lapse Rates over Norway

The slope lapse rates (SLR) were calculated for a whole annum and separately for summer and winter at every study site. SLRs were derived from four different datasets, (1) from original ERA5-Land, (2) from original seNorge, (3) from weather stations where available, (4) monthly SLR from a more complex model. The effects of differently derived SLRs on the performance of the downscaling procedure will be presented later in this section.

The results of the first approach revealed annual mean slope lapse rates ranging from – 4.1 ^{o}C/km (Bondhusbrea) to -7 ^{o}C/km (Engabreen), while winter and summer slope lapse rates are varying from -4.2 ^{o}C/km to -7.2 ^{o}C/km as of summer, and – 3.8 ^{o}C/km to -9.6 ^{o}C/km in the winter. These results demonstrate an increasing trend of SLR towards the north. This result is, in general, in line with findings of previous studies showing lower SLR at colder climate locations, which, consequently, is a sign of less surface melt of glaciers (Gardner et al., 2009). The above-described results, however, carry uncertainties of at least two origins. The reanalyzed temperature data and corresponding elevation values carry the potential for mistakes given the spatial resolution (~ 9 km) of the ERA5-Land climate reanalyzes dataset, which, in complex terrain, often results in inaccurate altitude and temperature values.

Subsequently, the considerable range of SLR measured based on an artificially set up profile facing the glaciers was belied by applying other methods to compute SLR. The next procedure used all the climate data grid cells and corresponding elevation values in a given range around the areas of interest. The results presented a customarily, less extensive variation of slope lapse rates over the study sites. Nevertheless, it produced anomalies, such as the SLRs revealed at Rembesdalskåka with an annual average of -3.9 °C/km, compared to the -4.6 °C/km estimated previous manner. At the northernmost location, Engabreen, this method revealed an SLR of -6.7 °C/km, which is in considerably better agreement with the SLR calculated from the three weather stations at Glomfjord, in the proximity of the catchment and the glacier, that demonstrates a slope lapse rate of -6.2 °C/km. However, the respective summer and winter SLR values still imply biases, most likely due to the uncertainties of the driving dataset, ERA5-Land.

Lastly, the SLR calculation supported by the seNorge observational dataset produced the most realistic results in terms of seasonal fluctuation and agreement with the conclusion of previous research. Regarding annual mean SLR, slope lapse rates extend from -5.8 °C/km (Austdalsbreen) to – 6.8 °C/km (Engabreen). At Engabreen, an outlet glacier of the Svartisen ice cap in the north of Norway, slope lapse rates demonstrate insignificant seasonal fluctuation and generally higher SLRs, a common sign of colder climate (Gardner et al., 2009). Based on the seNorge observational dataset, mean summer near-surface air temperature at Engabreen ranged between 5.1 °C and 7.1 °C, while winter temperatures varied in the -3.3 °C and -5.2 °C in the interim of the last five years. In opposition, the glaciers located in the geographical South of Norway, SLRs were lower and exhibited a broader spectrum of seasonal slope lapse rate values. Here, estimated slope lapse rates vary in the range of -5.8 °C/km to -6.3°C/km on an annual basis, -6.1 °C/km to -6.4 °C/km in the melting season, and -5.1°C/km to -6.0 °C/km during winter. The other end of the spectrum with the lowest SLR was measured at Austdalsbreen, a glacier arm located on the inland side of the Jostedalsbreen icecap with generally a high elevation between approximately 1200 m.a.s.l. and 1740 m.a.s.l. Summer mean temperature over the past five years moved in the frame of 3.6 °C to 6.8 °C, while during the winter, it was as low as -5.4 °C to -7.4 °C. Measured SLRs are in good agreement with the research of Jóhannesson et al. (2006), who derived SLR values through mass-balance modeling of Nigardsbreen, which is not far from the Austdalsbreen. Their research revealed a summer slope lapse rate of -5.8 °C/km at Nigardsbreen, in comparison with the -6.1 °C/km this study presents.

Location/ climate	Study site	Slope Lapse Rate (°C/km)	Summer SLR (°C/km)	Winter SLR (°C/km)
South – Continental	Austdalsbreen	- 5.8	- 6.1	- 5.1
South – Semi-maritime	Bondhusbrea	- 6.3	- 6.5	- 6.0
South – Continental	Rembesdalskåka	- 6.2	- 6.4	- 5.8
North – Maritime	Engabreen	- 6.8	- 6.7	- 6.7

Table 7: Temperature lapse rates over the four study sites in the thesis derived from seNorge.

4.3.2. Results of Downscaling ERA5-Land

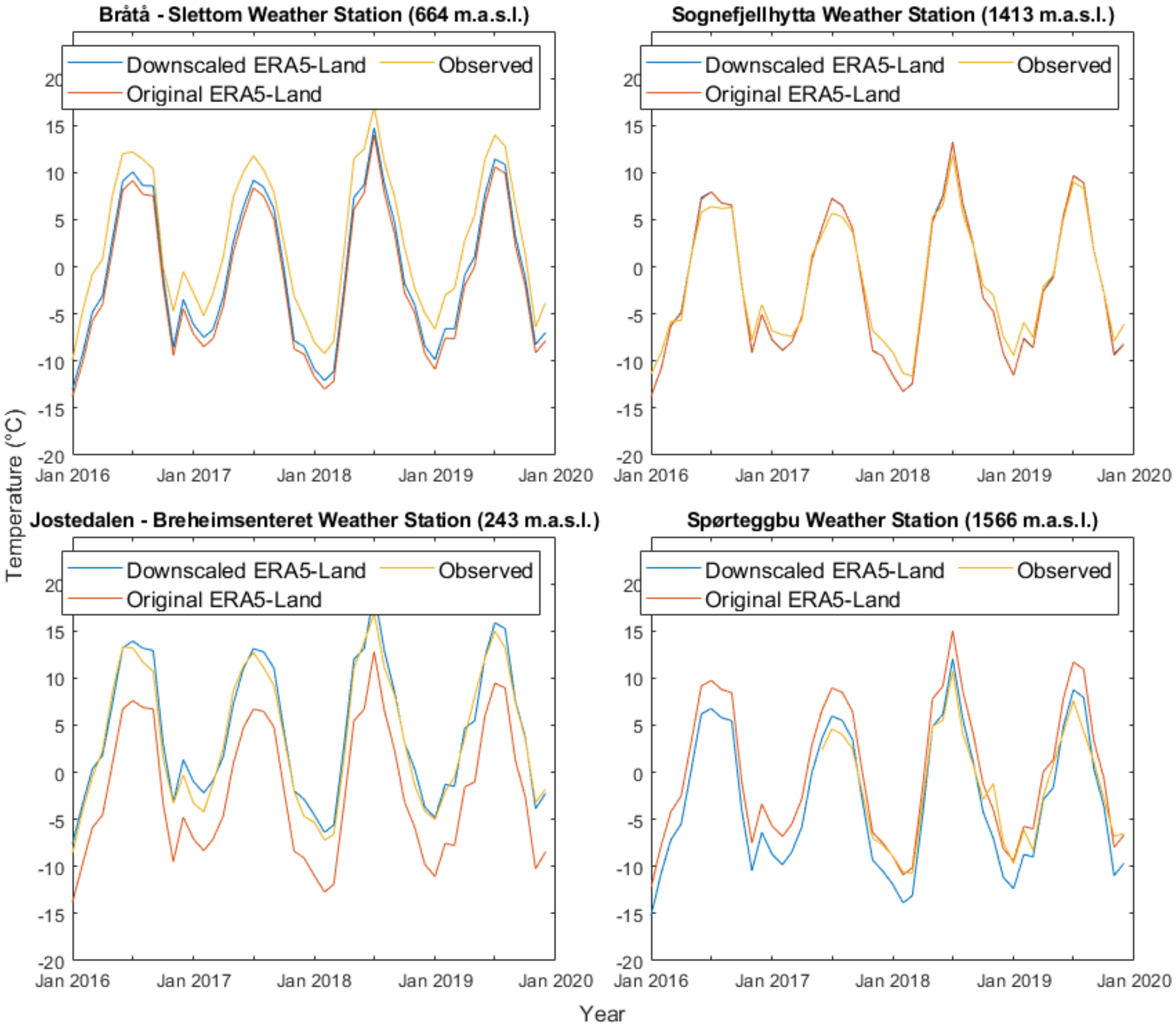
The temperature and precipitation derived from the state-of-the-art global reanalysis dataset ERA5-Land were downscaled from ~ 9 km to a 30 m spatial resolution using the topography of the global ASTER Digital Elevation Model. Both original and downscaled ERA5-Land weather variables were evaluated by comparing them to observed values at every study site in the reference period of 2016-2019. Since precipitation demonstrated substantial disparities between ERA5-Land and observed data, this subchapter will focus on evaluating the improvements in capturing temperature.

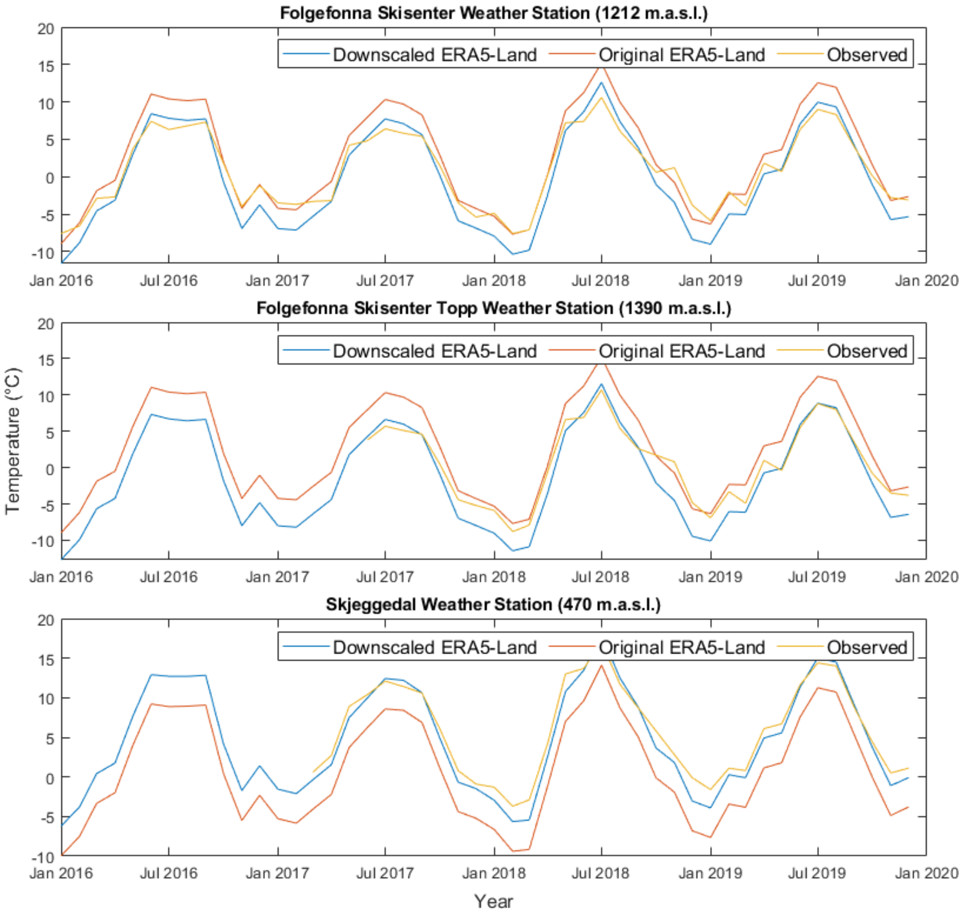
Findings of the downscaling procedure present a clear pattern, which is present at every study location. In general, the downscaling substantially improved the ERA5-Land temperature values in topographically complex circumstances. At Austdalsbreen (see Figure 15 first group of figures, the best results produced by the downscaling process appeared at low and medium elevations. At these altitudes, the downscaling output is in significantly better alignment with observations than the original ERA5-Land data. This is most likely due to the overestimation of altitude used during the assembly of the ERA5-Land reanalysis. In the complex terrain of Norway, the ~ 9 km resolution might be a considerable disadvantage. At higher elevations, however, the original ERA5-Land performs decently in winter, while the downscaling generated significant improvements for the ablation period. Furthermore, at high altitudes, the downscaling decreased quality in the winter season, which might be a consequence of using constant, annual mean SLR.

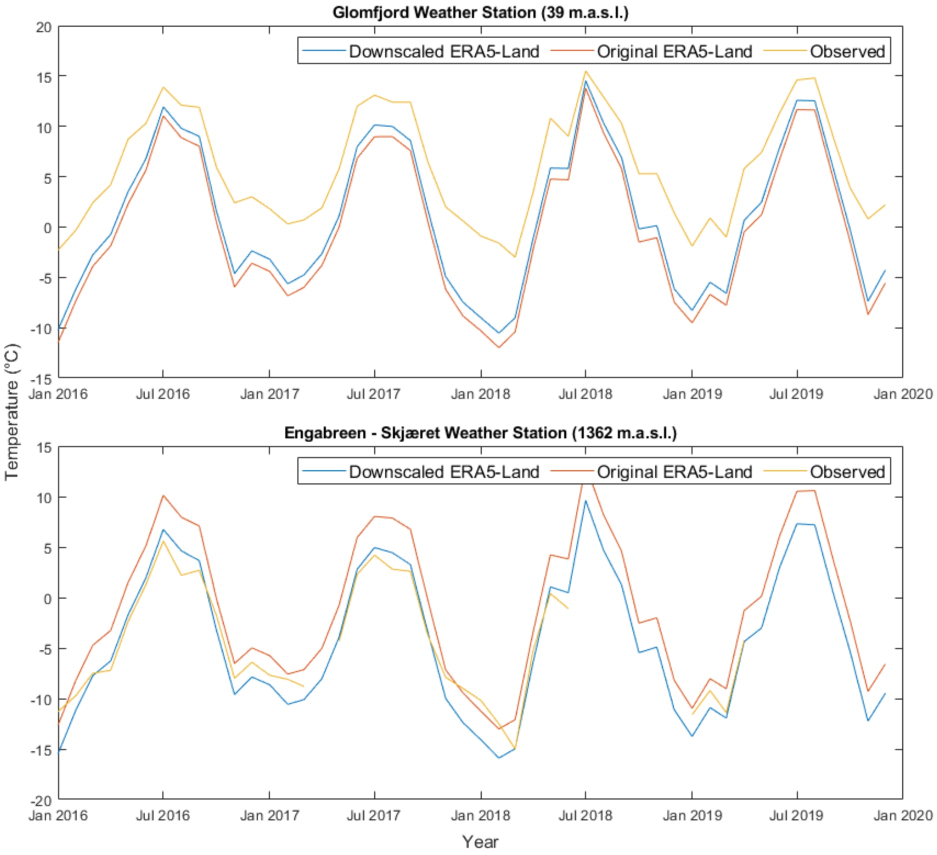
The assessment of the original ERA5-Land at Bondhusbrea (see Figure 15, second group of figures) displays an underestimation of temperature at low and mid-elevations. The downscaling procedure moderately improved the agreement with observational data, particularly in the melting season, which is the most crucial period for achieving the objectives set for this study. Nevertheless, there is still a noticeable disparity between observed data and ERA5-Land.

At Rembesdalskåka (Figure 15, last group of figures), the original ERA5-Land performs best at relatively high altitude, around 1200 m.a.s.l. In high elevations, the downscaling process resulted in marginally overestimated summer temperature while improving performance in the winter. On the other hand, improvements caused by downscaling increased with decreasing in elevation.

In the glaciological north, at Engabreen (see Figure 15, third group of figures), the weather stations represent the two ends of the spectrum in terms of altitude. Evidently, downscaling improved the performance of climate reanalysis substantially at both WS locations, principally for the summer season.




Folgefonna Skisenter Weather Station (1212 m.a.s.l.)
Folgefonna Skisenter Topp Weather Station (1390 m.a.s.l.)
Skjeggedal Weather Station (470 m.a.s.l.)
Downscaled ERA5-Land
Original ERA5-Land
Observed
Temperature (°C)
Year
20
15
10
5
0
-5
-10
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020


Glomfjord Weather Station (39 m.a.s.l.)
Engabreen - Skjæret Weather Station (1362 m.a.s.l.)
Downscaled ERA5-Land
Original ERA5-Land
Observed
Temperature (°C)
Year
20
15
10
5
0
-5
-10
-15
-20
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020

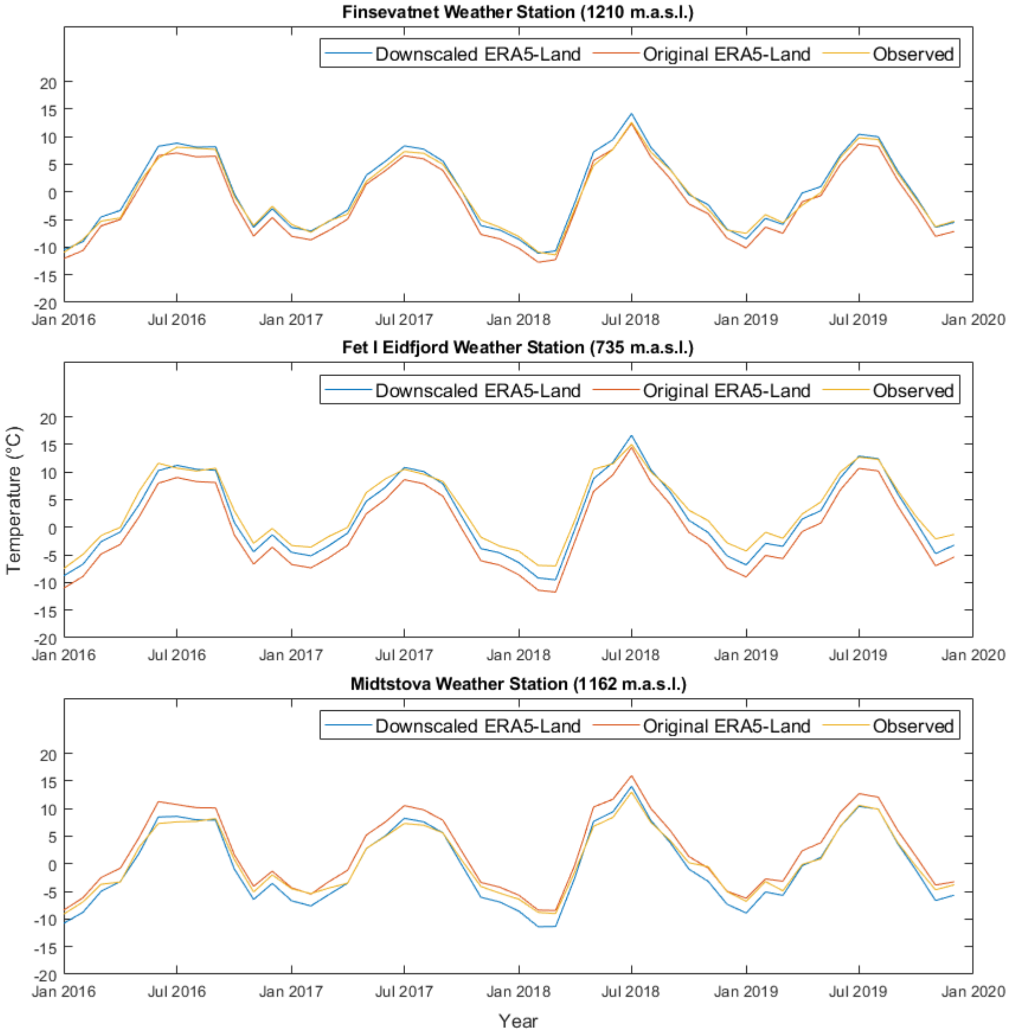


Figure 15 - Downscaled ERA5-Land plotted with original ERA5-Land air temperature and observations at the four study site, Order of figures: Austdalsbreen, Bondhusbrea, Engabreen and Rembesdalskåka.

4.3.3. The Impact of SLR on Downscaling

The application of various slope lapse rates (SLR) for downscaling ERA5-Land revealed a few intriguing results.

The SLRs were calculated from four different datasets, (1) from original ERA5-Land for every location, (2) from literature (3) from weather stations at Engabreen, (4) and monthly SLRs from a more complex model at Rembesdalskåka. The impact of using different SLRs will be presented with two cases, Engabreen and Rembesdalskåka, where additional options for computing SLRs were available beside ERA5-Land and seNorge based SLRs.

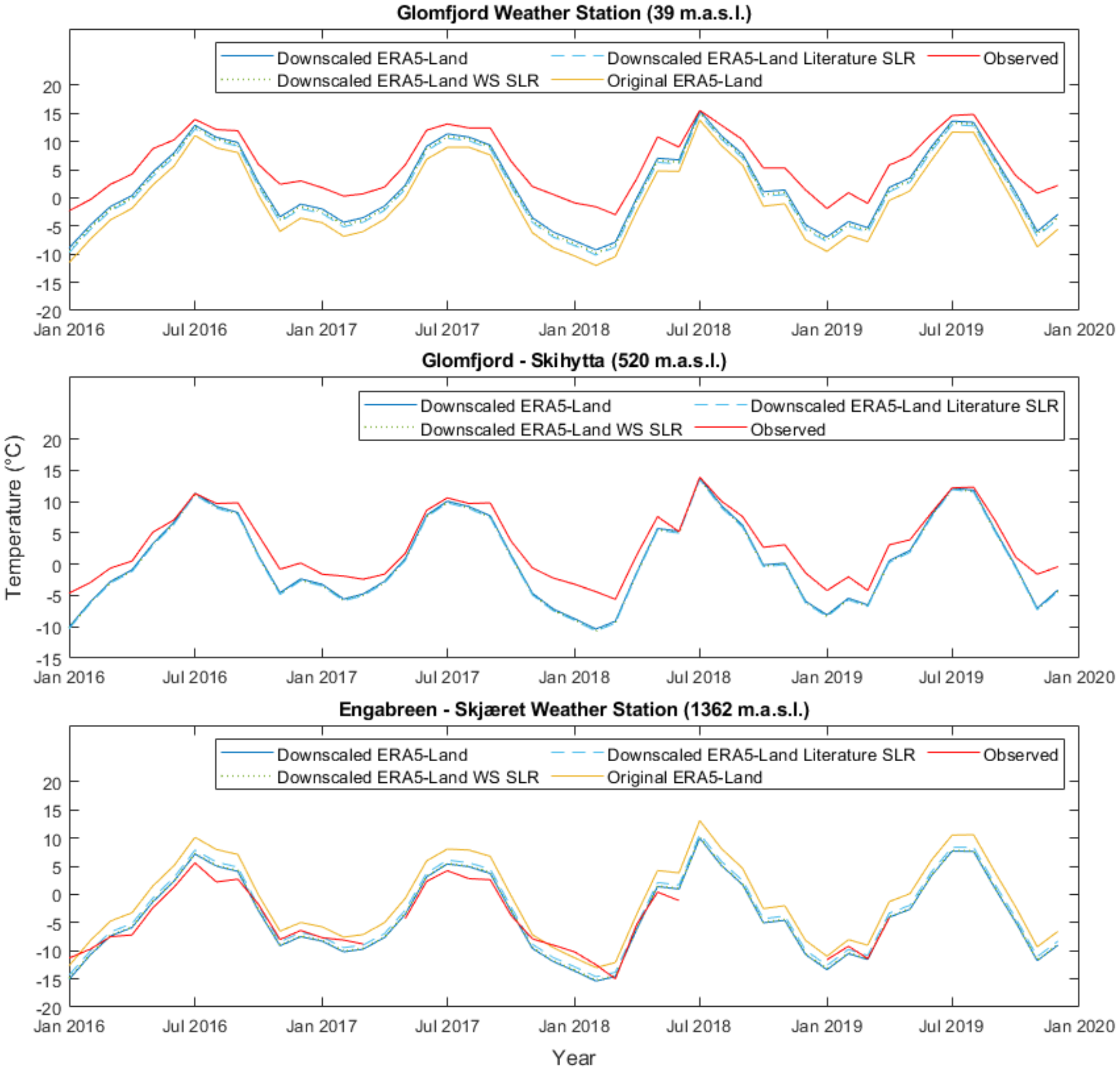


Figure 16 - Assessment of downscaling near-surface air temperature with lapse rates derived from differing sources. The first version of downscaling was forced with temperature lapse rates obtained from gridded ERA5-Land data, the second version from a weather station triplet located at three different altitudes nearby each other, whereas the last lapse rate was adopted from literature.

The involvement of several SLR brought improvements to a varying degree. At Engabreen, all three tested SLR are static throughout the year. Therefore, they caused the same patterns of improvements but to varying extent. Downscaled ERA5-Land captured observations best when SLRs obtained from original ERA5-Land were used (see Figure 16).

On the other hand, at Rembesdalskåka, monthly SLRs delivered the most notable improvements for non-ablation period, however, at the Midstova and Finsevatnet weather stations (see Figure 17), which are located above 1100 m.a.s.l., the process resulted in better agreement between modeled and observed summer temperatures as well, showing good potential for enhancing the performance of a global dataset in a local, topographically complex context.

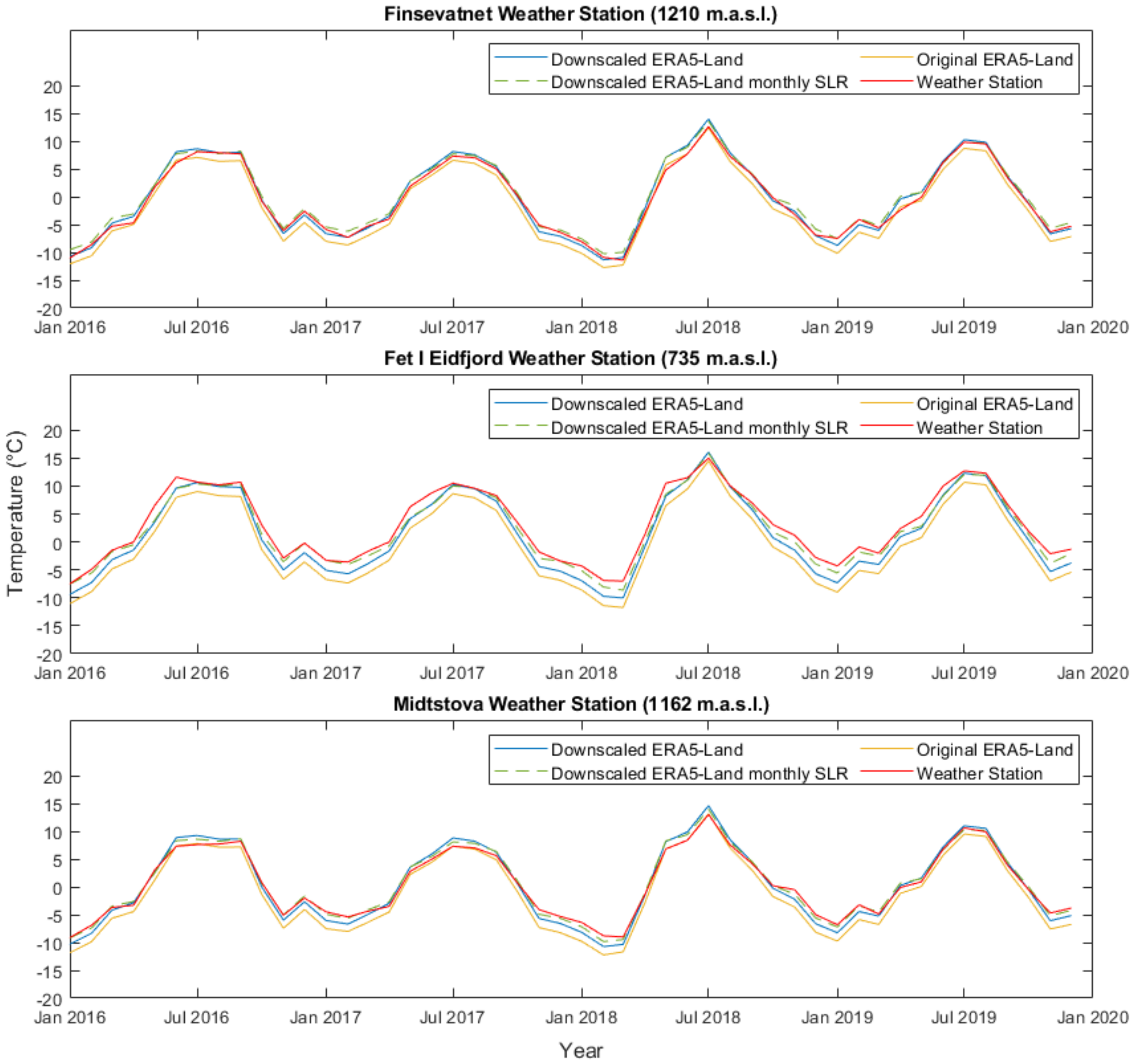


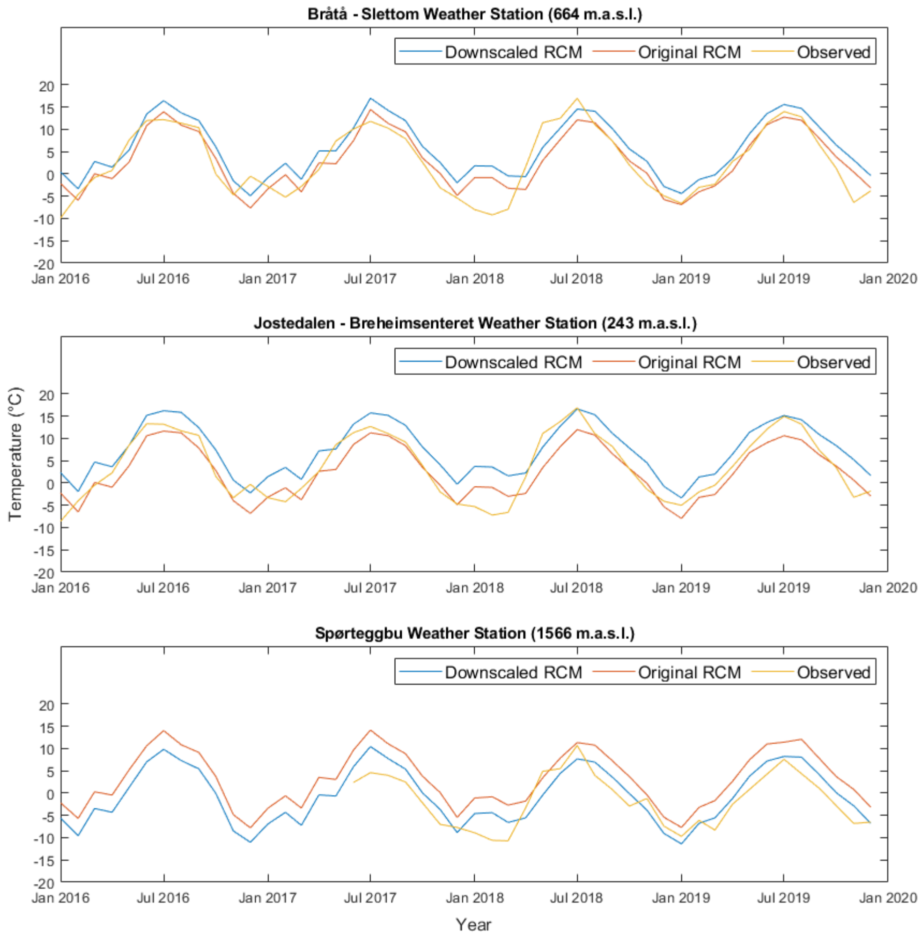
Figure 17 – Similarly to the previous figure, downscaled air temperature forced with slope lapse rates derived from various sources are plotted together with observations and the original ERA5-Land dataset. The first version of downscaling was forced with temperature lapse rates obtained from gridded ERA5-Land data, whilst the second version of lapse rates are generated by a complex runoff model ran as part of the GOTHECA project.

4.3.4. Results of Downscaling RCA4 Regional Climate Model

The improvements brought by downscaling of the regional climate model (RCM) RCA4 were evaluated with the same weather stations as ERA5-Land. Climate data from the RCM was downscaled from an original ~ 12 km to 30 m spatial resolution. The topography adjustment component of the downscaling was forced with the global ASTER digital elevation model.

It was presented in the previous Section that the use of static SLRs in the downscaling procedure will influence the output only marginally. Therefore, a static SLR was used for downscaling RCM projections. The SLR derived from seNorge was in the best agreement with SLR obtained from weather stations and literature; thus, this was deemed the most realistic option, and it was used for downscaling the RCM projections. Since the RMSE statistical test (see Section 4.2) revealed exceedingly poor model performance for precipitation, precipitation analysis is neglected in this subchapter.

Based on plotting the downscaled and original temperature data generated by RCA4 (see Figure 18) it becomes evident that improvements are most prominent at high elevations. Downscaling resulted in moderate improvements at mid-altitudes and further decrease towards low elevation areas. Seasonally, the implementation of the topography factor influenced the performance for both summer and winter temperatures. Overall, the statistical downscaling positively impacted the ability of the RCM to determine climate patterns spatially and seasonally precisely. The results of comparing original RCM and downscaled RCM skills with observations is presented in Figure 18.



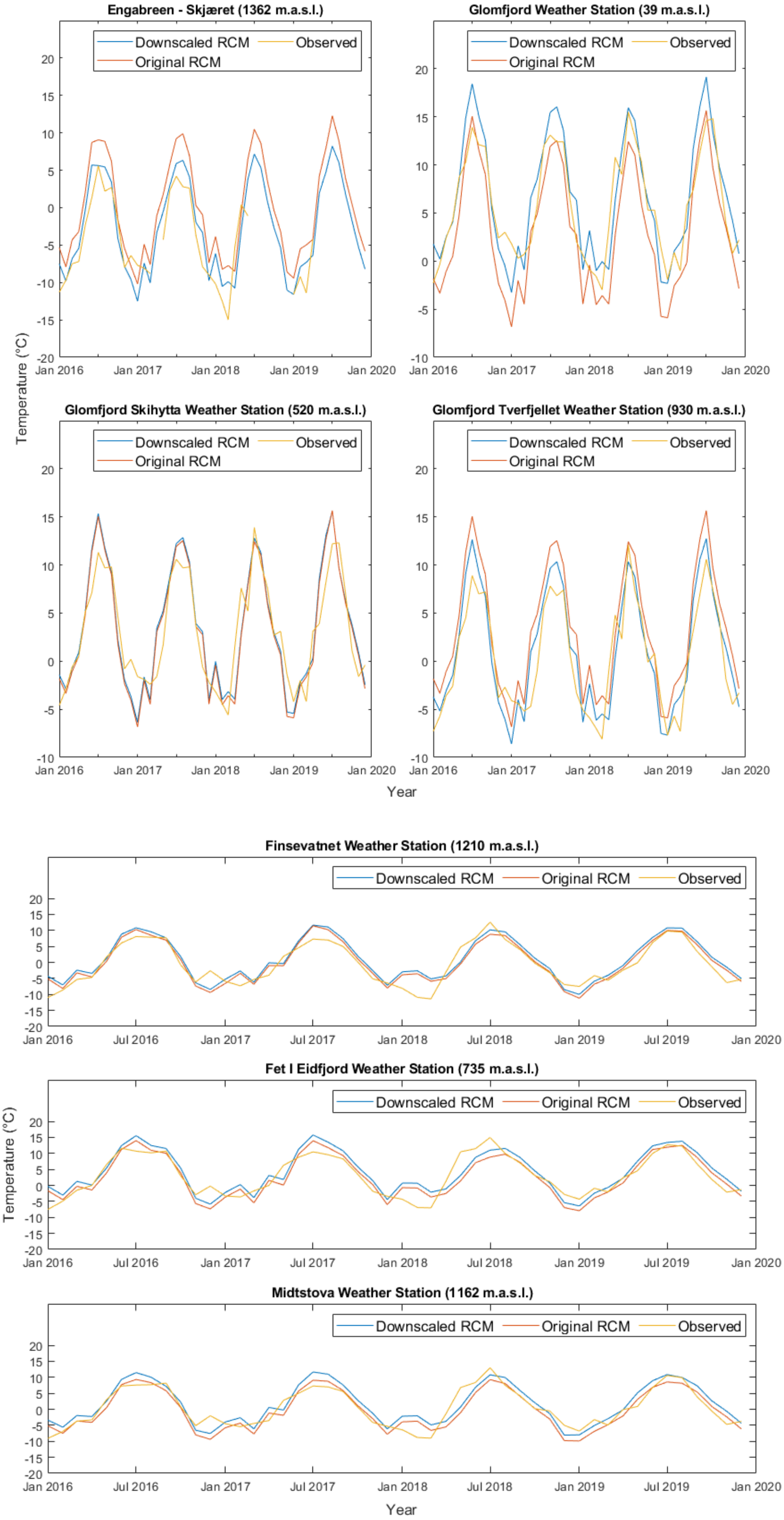


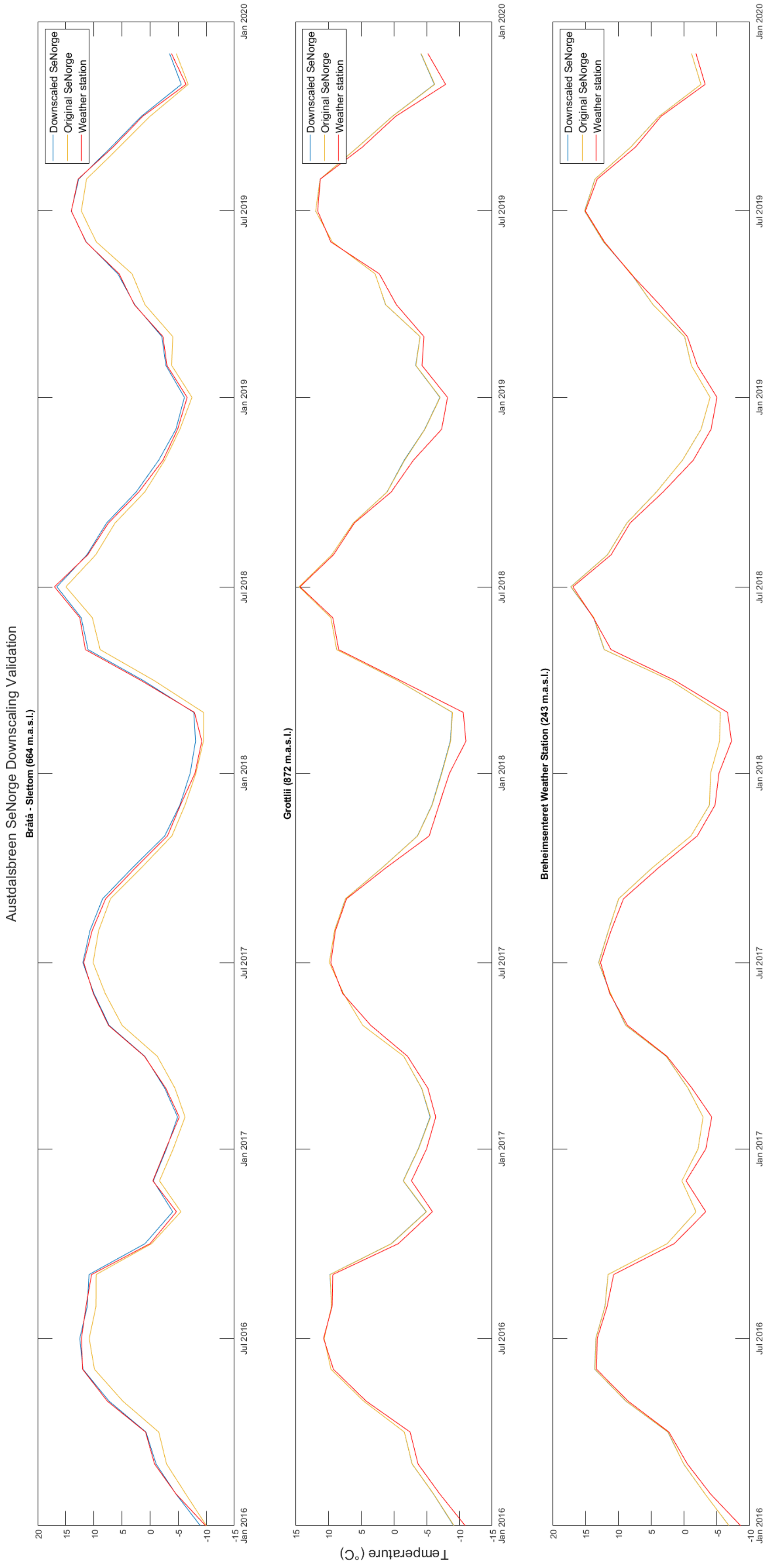
Figure 18 - Downscaled RCA4 temperature plotted with original RCA4 air temperature and observations at three study sites, Austdalsbreen, Engabreen and Rembesdalskåka.

4.3.5. Results of Downscaling seNorge

The original seNorge gridded temperature and precipitation fields carry a 1 km spatial resolution, which was downscaled to 10 m using the Norwegian 10-meter Digital Terrain Model (see Section 3.1.7). In this subchapter, the main emphasis will be on the improvements brought by downscaling seNorge temperature records since climate data products seem to struggle with precisely capturing precipitation regimes.

Since seNorge is created through a statistical interpolation of weather station observations all over Norway, good agreement was anticipated between downscaled and observed variables. In general, downscaling improved seNorge derived air temperature and precipitation records marginally. The most noticeable enhancement took place at mid-elevations (around 500 m.a.s.l.) at every location. The downscaling procedure also improved the ability of seNorge to capture summer peaks in temperature. At Austdalbreen, this improvement is apparently displayed at the Bråtå-Slettom weather station, located at 664 m.a.s.l. (see Figure 19). Downscaling of temperature and adjustments for elevation using slope lapse rates resulted in a better agreement with observations at mid-altitudes almost throughout the whole reference period at every studied glacier location. On the other hand, at Rembesdalskåka, in a topographically less diverse environment, the original seNorge replicates temperatures almost perfectly at every WS location; thus, the downscaling resulted in negligible improvements, mostly enhancing performance in capturing winter minimum temperatures.

As for precipitation, the downscaling process contributed to very light improvements. However, seNorge replicates observations relatively well initially with a general overestimation of peak precipitation. Nonetheless, original seNorge significantly overperforms original ERA5-Land in capturing precipitation in Norway’s mountainous regions, which comes as no surprise since seNorge is based on observations and produced in higher spatial resolution.


Austdalsbreen SeNorge Downscaling Validation
Bråtå - Slettom (664 m.a.s.l.)
Grottlii (872 m.a.s.l.)
Breheimsenteret Weather Station (243 m.a.s.l.)
Downscaled SeNorge
Original SeNorge
Weather station
Temperature (°C)
20
15
10
5
0
-5
-10
-15
Jan 2016
Jul 2016
Jan 2017
Jul 2017
Jan 2018
Jul 2018
Jan 2019
Jul 2019
Jan 2020

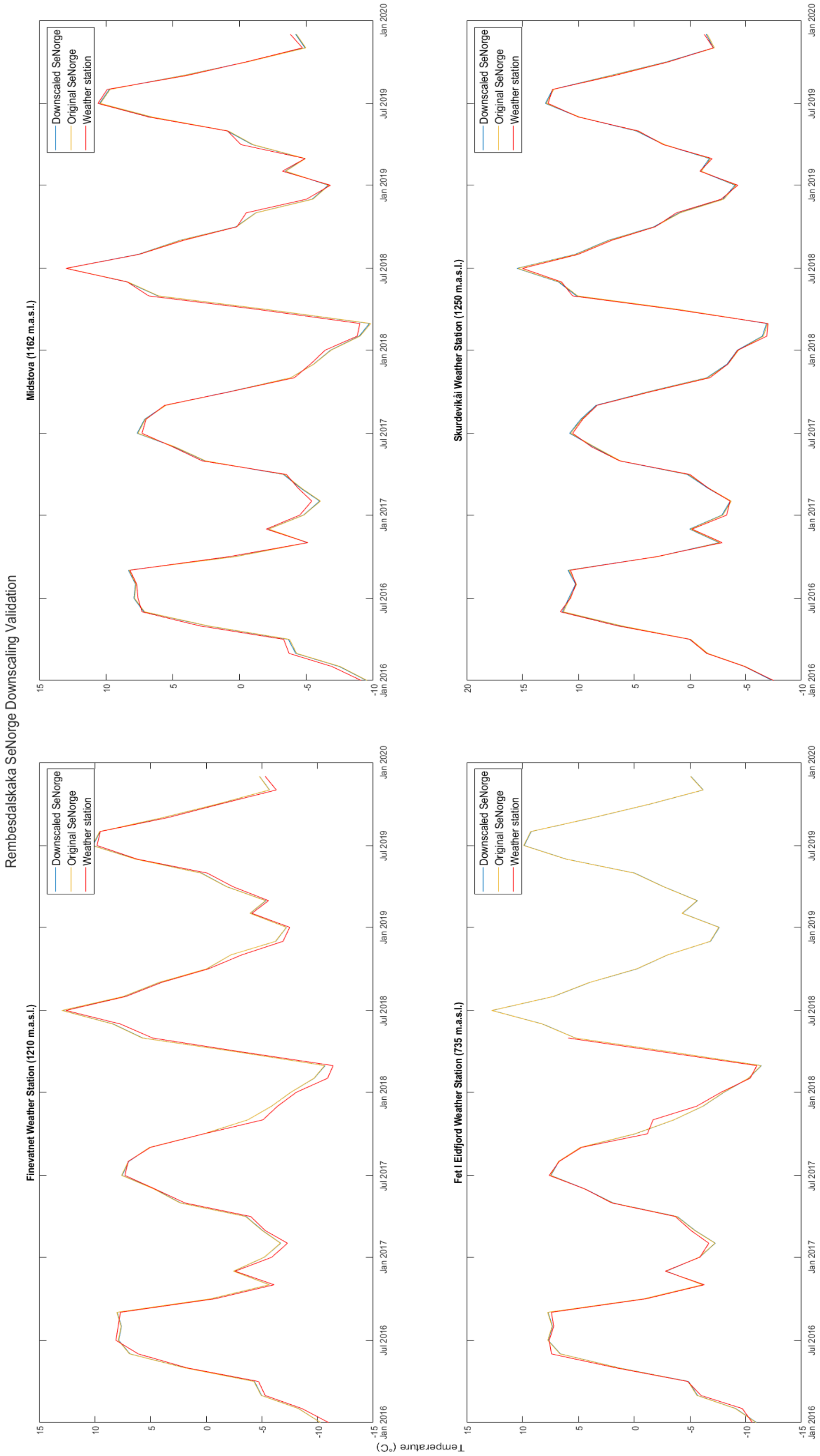


Figure 19: In the previous page: downscaled and original seNorge plotted with observations in 2016-2019 at Austdalsbreen. Current page: Original and downscaled seNorge temperature plotted with observations at Engabreen.

4.4. Results of the PDD model

4.4.1. Validating Model Performance

In this section, the PDD model performance will be evaluated with mass balance measurements and runoff observations. Additionally, a comparison is developed between model outputs produced by using downscaled seNorge observational climate data, ERA5-Land global climate reanalysis, and RCA4 regional climate model.

The approach for calculating PDDs was developed by Calov and Greve (2005) and it showed good potential for correctly predicting the sum of positive degrees from monthly temperature data (Hallé, 2020). Hence, the validation of the PDD sum component (see Section 3.5.1) was neglected in this study. Instead, the validation of the model output was performed by comparing modeled mass-balance to measured values by implementing a correlation of coefficient (cv) test (see Section 3.5.3), and modelled runoff to observed values by calculating the Nash-Sutcliffe (NS) coefficient (see Section 3.5.3).

Long-term mass balance measurements were available for three glaciers, Austdalsbreen for the period of 1988-2019, Engabreen in the time range of 1969-2019, and with the longest mass balance record, Rembesdalskåka between 1962-2019. At the same time, there are relatively few gauging stations located near glaciers. The two locations with extensive observed discharge records are Engabreen (1969-2019) and Bondhusbrea (1963-2019). Subglacial tunnels are installed at both glaciers for transferring glacier meltwater to hydropower plants.

Complications occurred in validating the source of the runoff, as this requires observational data from subglacial tunnels. This hindrance was resolved at Engabreen since records of daily sub-glacial tunnel inflow data are available. Unfortunately, such data is not available at Bondhusbrea, making observations ineligible to validate the model accurately at this specific location. Hence the observations obtained from the gauging station at Bondhusbrea were only used to determine if the model captures seasonal trends correctly. At Engabreen, validation was quantified by the Nash-Sutcliffe statistical test for the period prior to the opening of the sub-glacial tunnel (1981-1993).

Runoff observations

Downscaled seNorge, ERA5-Land, and the historic period simulations of the selected bias-corrected version of the RCA4 RCM were used as input temperature and precipitation to run the PDD model for the period of 1981-2019. Results of validating the model output with observed runoff at Engabreen are visualized in Figure 20. The graphs imply that the PDD model successfully replicates seasonal cycles in runoff and predicts discharge amount reasonably well with every type of input. Nevertheless, there are visible differences between the extent of effectiveness of different model outputs.

Based on the observations derived from the gauging station at Engabrevatnet, peak flow commonly occurs in July-August, whilst there is a slow and subtle shift during the second half of the 2000s, where the timing of the largest amount of discharges drifts to August-September more often than earlier. In addition, total discharge from the basin marginally increased in the period of 1995-2010 compared to the previous decades. In terms of the seasonal cycle the total amout of monthly discharge, and the shift in peak flows were best modeled when the model was forced with seNorge.

When quantifying model performance, seNorge produced a NS coefficient of 0.85, which is considered an adequately good match between modeled and observed values. In contrast, ERA5-Land resulted in a considerably lower NS coefficient of 0.66 at Engabreen, which was expected following the generally poorer performance of the original ERA5-Land to capture observed temperature and precipitation compared to seNorge. The historic RCM model output performed better than the ERA5-Land driven simulation. This is confirmed by a Nash-Sutcliffe coefficient of 0.71 in contrast to 0.66. Despite difficulties with validating model performance at Bondhusbrea, figures showed that the PDD model effectively replicated seasonal variations and the timing of peak discharge in general with similar patterns to that revealed at Engabreen (seNorge model output most precise).

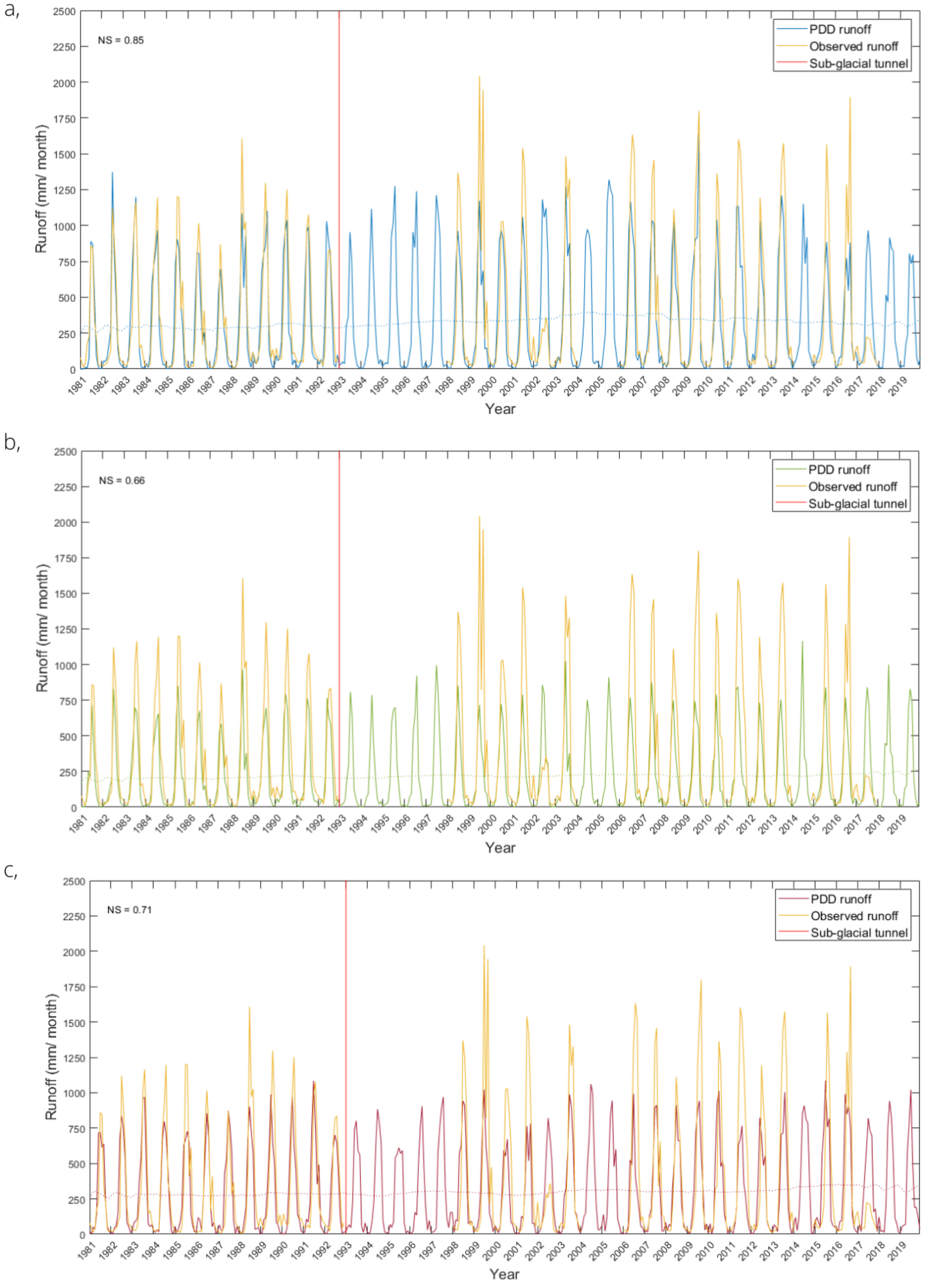


Figure 20 - Validating PDD model performance with runoff observations obtained from gauging stations at Engabreen. The three graphs: (a) seNorge based PDD run; (b) ERA5-Land based PDD run; (c) Regional climate model RCA4 based model run. The red vertical line indicates the opening of the sub-glacial tunnel. Accurate validation may be problematic after that period therefore the Nash-Sutcliffe coefficient (NS) was only computed for the period of 1981-1993.

Mass balance measurements

Extensive mass balance records were available for Austdalsbreen, Engabreen, and Rembesdalskåka, leaving the validation of model performance at Bondhusbrea unfeasible. The validation of PDD model skills to replicate measured seasonal mass balances was quantified by the coefficient of variation. Repeating the tendency shown during the validation with runoff observations, the seNorge model version noticeably outperformed the other versions of model runs (see Table 8). This is verified by consistently lower coefficients of variation at every location. Thus, the conclusion: seNorge is the most reliable source of climate data for modeling hydrology at glacierized basins in Norway with the specific approach used in this study.

When analyzing the performance of the PDD model to replicate seasonal mass balances across the study sites, it is evident that the model captures measurements best at Engabreen. This is most likely a consequence of the used model parameters. Ice and snowmelt factors used in the melt component of the PDD model were adopted from literature. The parameters applied at Engabreen are from more recent research; hence, they are presumably more accurate.

Table 8 - Coefficient of variation as a measure to quantify how well mass balance is modelled by the PDD model compared to mass balance measurements from NVE.

Location	**seNorge** summer/ winter	**ERA5-Land** summer/ winter	**RCA4** summer/ winter
Austdalsbreen	0.28 / 0.27	0.34 / 0.30	0.50 / 0.37
Engabreen	0.19 / 0.19	0.30 / 0.25	0.29 / 0.34
Rembesdalskåka	0.23 / 0.32	0.32 / 0.39	0.45 / 0.40

seNorge PDD model output and measured seasonal mass balances are plotted together in Figure 21. In general, the PDD model predicts fluctuations of seasonal balances to a relatively good extent. However, summer balances are commonly overestimated in the model, implying a deficiency in the melt component. The graphs indicate better predictive skills to capture winter balance in the first half of the evaluated period at Engabreen and Rembesdalskåka. Efficiency of replicating winter balance frequently decreases from 2002-2005 with considerable differences between modeled and observed mass balance at Rembesdalskåka during the last ten-fifteen years of the reference period. Summer balances are generally well-modeled at Engabreen and Rembesdalskåka. In contrast, there are substantial discrepancies between modeled and measured summer balance at Austdalsbreen, particularly after 2000.

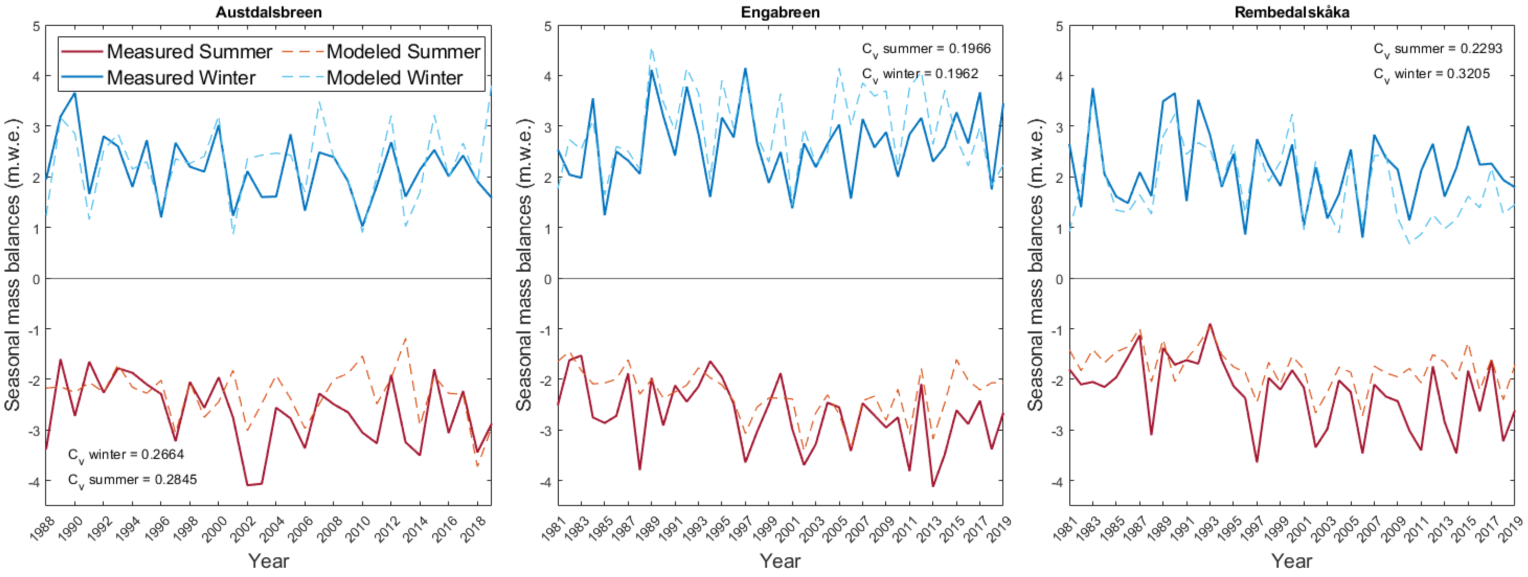


Figure 21 - The performance of seNorge based PDD model to replicate mass balance records plotted against mass balance measurements with corresponding coefficient of variation (C_v) values. Source of mass balance data: NVE.

4.4.2. Total Discharge

Since the validation of the PDD model indicated that the seNorge version of the PDD model output is the most capable of accurately replicating runoff observations and mass balance measurements, the remaining subchapters will be based on that version of the model.

Examining annual total discharge on a catchment level displays significant differences between the four study basins. All catchments had an increase in runoff until approximately 2000. However, while streamflow sustained an increasing tendency at Engabreen and a moderately increasing progression at Bondhusbrea, annual discharge dropped at Austdalsbreen and Rembesdalskåka after the turn of the century. The decreasing tendency continued during the period 2000-2010 both at Austdalsbreen and Rembesdalskåka. These two runoff catchments exhibit noticeably similar variations in yearly discharge sums with a prominent increase after 2012. At the same time, yearly runoff maintained a steady but slow increasing tendency at Bondhusbrea during the second half of the examined period (2001-2019). At Engabreen, a negative shift in annual discharge sums occurred recently, starting around 2010, but after a sharp decline, annual runoff stablised around pre-2000 values. However, in general, discharge has intensified at every studied basin to a varying extent since the 1980s (see Figure 22).

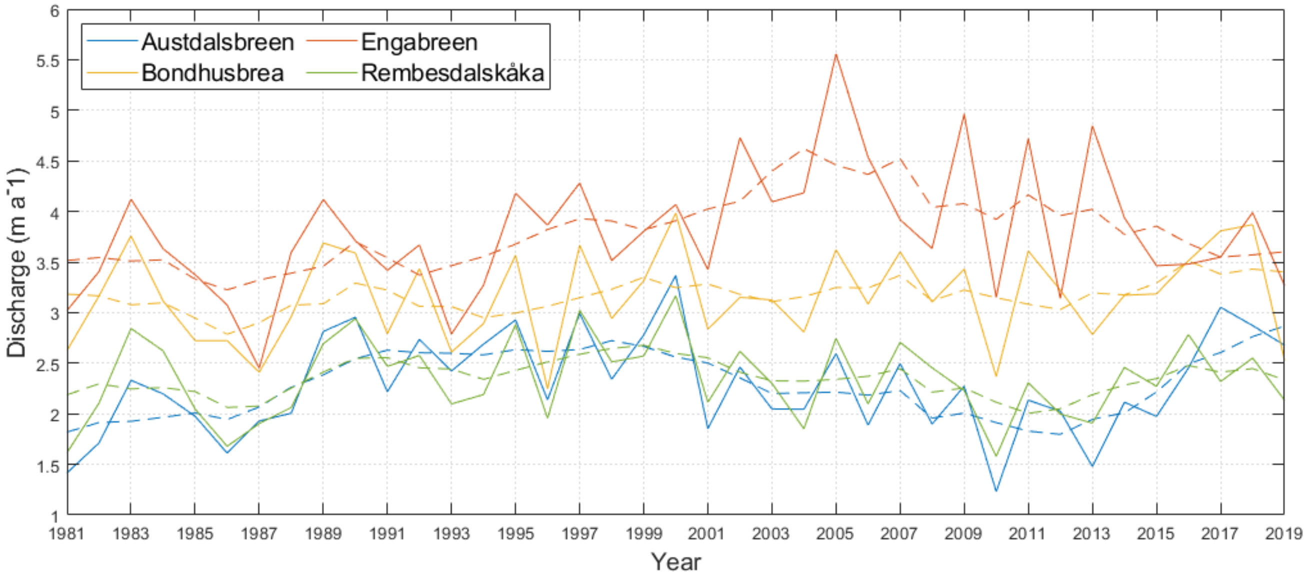


Figure 22 - Annual total discharge of the studied catchments along with the 5-year moving mean.

When segmenting the 1981-2019 period into two halves and examining runoff spatially, it becomes evident that the contribution of the glacierised area to total runoff increased at every study site (see Figure 23). Similarities arise again between Austdalsbreen and Rembesdalskåka and between Engabreen and Bondhusbrea, which indicates that runoff at the two more continentally located glaciers, Austdalsbreen and Rembesdalskåka, varied within similar ranges. The share of different sources shifted essentially in both catchments in 2001-2019 compared to 1981-2000. The glacier area stands out more eminently in the second period (2001-2019) than in the first half of the modeled period (see Figure 23); suggesting that the share of glacier melt intensified considerably.

In contrast, at Bondhusbrea and Engabreen, the proportion of runoff is more smoothly distributed across the entire basin in 2001-2019; implying a growing share of glacier melt proportionally to total runoff but to a lesser extent than at Austdalsbreen and Rembesdalskåka.

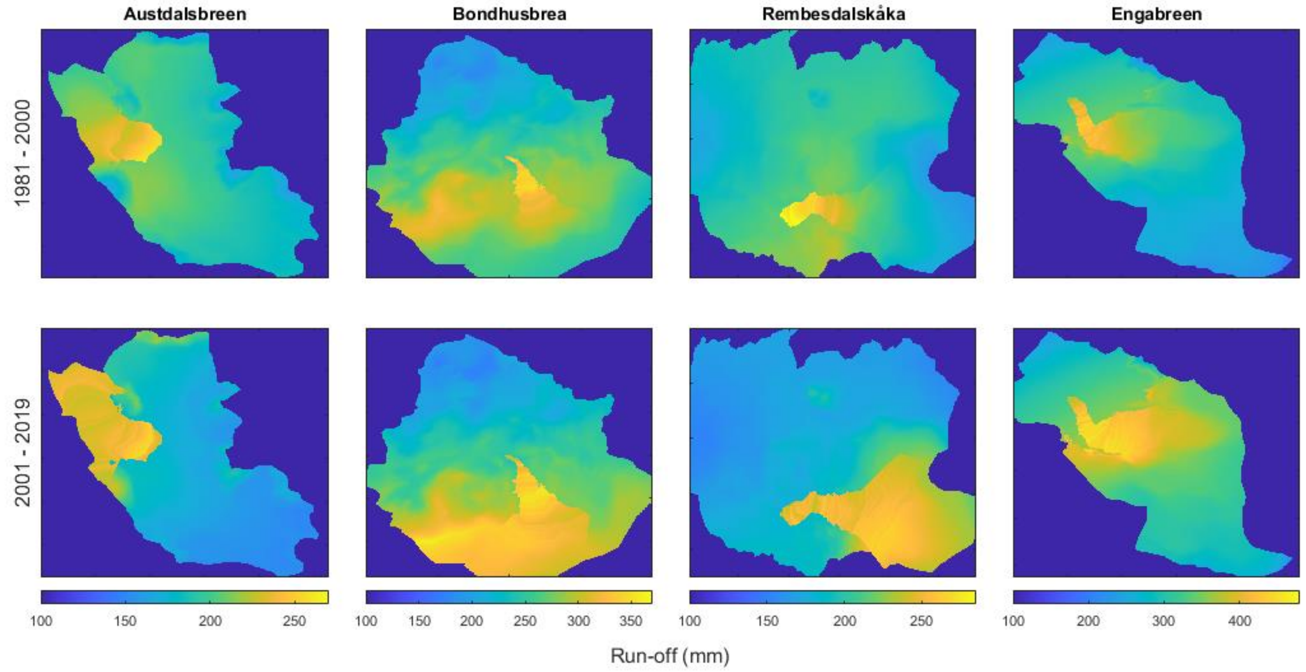


Figure 23 - Total mean runoff for two periods, upper line: 1981-2019; bottom line: 2001-2019 in each catchments.

4.4.3. Seasonal Distribution of Runoff and Contribution of Sources

Climate change may have a significant impact not only on annual total discharge in glacierized catchments but on the timing of peak flows as well. Abrupt shifts in the timing of significant discharge events may lead to an increased risk of flooding and necessitate swift adjustments in hydropower production and reservoir control.

This subchapter will partly focus on the seasonal distribution of discharge, presented in Figure 24. In addition, contributing components of runoff will be evaluated in this section. The seasonal contribution of various runoff sources is presented in Figure 24, whereas the long-term tendencies in the variations of different sources are shown in Figure 25. The studied period was divided into two halves, 1981-2000 and 2001-2019, since earlier analysis in this study revealed (see Figure 22) that extensive variations began at the turn of the century.

Austdalsbreen is located on the eastern slopes of the Jostedalsbreen in relatively continental conditions. Thus, receiving less precipitation than other glaciers closer to the ocean. Temperature fluctuation since 1957 were moderate with a major cooling in the 1980s with increasing temperatures since then (see Section 4.1). Discharge in the basin begins in May in 1981-2000, while it shifted to mid-spring with intensified April discharge in 2001-2019. Runoff peaks in July on average (~ 1.5 m) both in 1981-2000 and 2001-2019. The most significant share of ice melt can be observed at Austdalsbreen out of all the studied glaciers. The proportion of direct glacier ice melt is highest in July and August with only minor ice melt prior and after during the period1981-2000. The contribution of glacier melt increased significantly in July and August throughout 2001-2019. A general rise in the proportion of rain in total runoff can be noticed from the first (1981-2000) to the second period (2001-2019). Generally, runoff in August and September reduced after 2000, while it slightly intensified in May-July with a shift towards snow and ice melt from the glacier. This is supported by the spatial analysis of runoff in the corresponding period (see Figure 23), which implies a larger share of glacier contribution. In September, the ratio of liquid precipitation increased considerably in 2001-2019 compared to 1981-2000.

Another location with similar climatic conditions to Austdalsbreen is Rembesdalskåka. In general, the contribution of glacier melt (snow and ice) begins in May throughout the whole study period and discharge peaks in July with circa 1.8 m/month on average. The share of rain is gradually growing from May until September when it reaches it peaks in both examined periods. A major increase in rain contribution can be observed, mainly in September, after 2000. Generally, discharge at Rembesdalskåka was more distributed over the whole calendar year in 2001-2019 than before. In July and August, runoff decreased in 2001-2019 compared to 1981-2000, whilst discharge in May, June, and September intensified, primarily due to an increase in snowmelt on glacier surface and rain.

One intriguing aspect of examining the portion of contributing runoff sources at Rembesdalskåka is the abrupt shift in the dominance of snowmelt (basin only). During the first twenty years (1981-2000), snowmelt from the basin area carries the most significant influence on discharge from May to August. In the period of 2001-2019, however, the contribution of glacier melt (snow and ice combined) comprises substantially more extensive portions of total runoff in July-August compared to 1981-2000. Actual glacier ice melt contributed only a minor portion of total runoff in 1981-2000, while it slightly increased in 2000-2019. Considering long-term variations (see Figure 25) snow (basin only) remained the largest contributor to runoff throughout the past 40 years. Nevertheless, a decreasing conversion in snowmelt contribution can be observed between 1995 and 2019 when it drops from approximately 75% to 65%, whereas at the same time, the magnitude of glacier surface melt and rain enhanced by 5-7%.

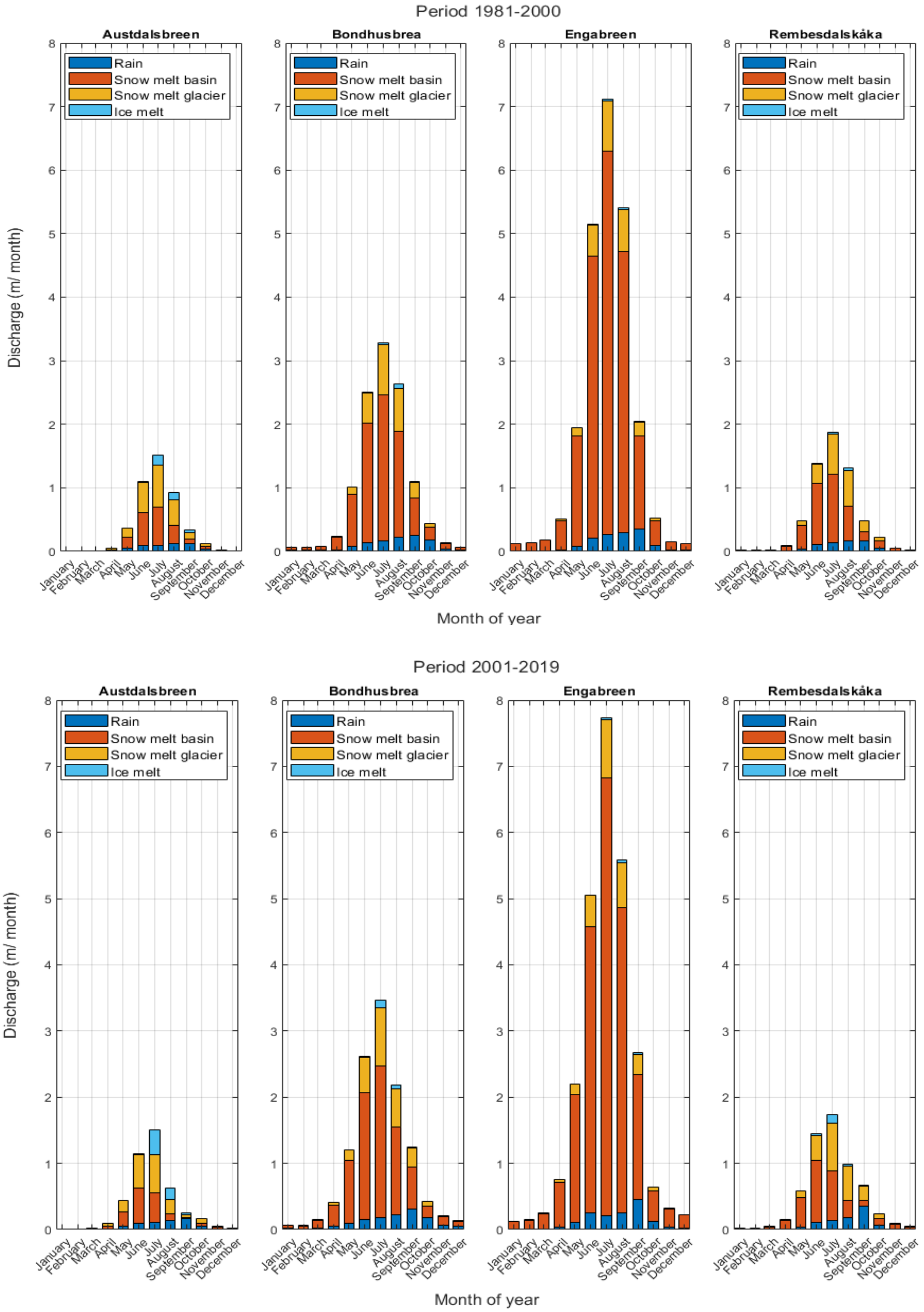


Figure 24 - Seasonal distribution of runoff and the contribution of rain, snow melt (separately in the basin and on the glacier) and glacier ice melt, averaged in the periods of 1981-2000 (upper figure) and in 2001-2019 (bottom figure).

]

Moving towards more maritime climatic conditions, Bondhusbrea is an outlet glacier that lies on the west side of the Folgefonna ice cap. Annual precipitation sums are significantly higher here compared to Austdalsbreen and Rembesdalskåka. The peak flow occurs in July consistently throughout the whole period of 1981-2019. However, there is a minor increase in July discharge from 3.2 m/month (1981-2000) to 3.5 m/month (2001-2019). A general increase in discharge can be observed from 1981-2000 to 2001-2019. The most prominent increase in discharge emerged during May-July and in September, whereas the August runoff reduced. Melting of snow is an all-year-long phenomenon in the basin, whilst rain contribution gradually increases from April to September. During the melting season - from May to September - the proportion of snowmelt is dominant both during 1981-2000 and 2001-2019 (see Figure 25). The share of snowmelt in the total runoff started to diminish around 1995, while the contribution of rain began to increase simultaneously. The contribution of glacier melt – ice and snow combined – fluctuated around 7-8% during the whole examined period 1981-2019 (see Figure 25).

At the northernmost location, at Engabreen, total annual discharge exceeds the other catchments throughout the entire period (1981-2019; see Figure 22). Engabreen is a maritime glacier located in the Arctic-circle. The catchment is characterized by high summer temperature and significant winter precipitation (see Section 4.1). Like other basins, runoff reaches its highest volume in July with an average of approximately 7.1 m/month in the first twenty-year period, while it increased by circa 9% in 2000-2019. As the melting season progresses from May to September, the ratio of rain increases as well.

Intriguingly, however, the average proportion of rain in the total runoff reduced from the first 20 years to the second period, except for September. Direct glacier surface melt began in May and was highest in July throughout 1981-2019. Glacier ice melt contribution demonstrated a minor increase from 1981-2000 to 2001-2019, mainly in July and August. Runoff became more distributed over the entire calendar year in 2001-2019, with the most significant increase shown during autumn. In general, the contribution of snowmelt increased between 1981-1995 and varied around 60-70%, whilst it began to decrease afterward. Rain mirrored this tendency with a recent increasing inclination. Lastly, the direct contribution of glacier melt to the total runoff fluctuated moderately at Engabreen, with proportion consistently around 20%.

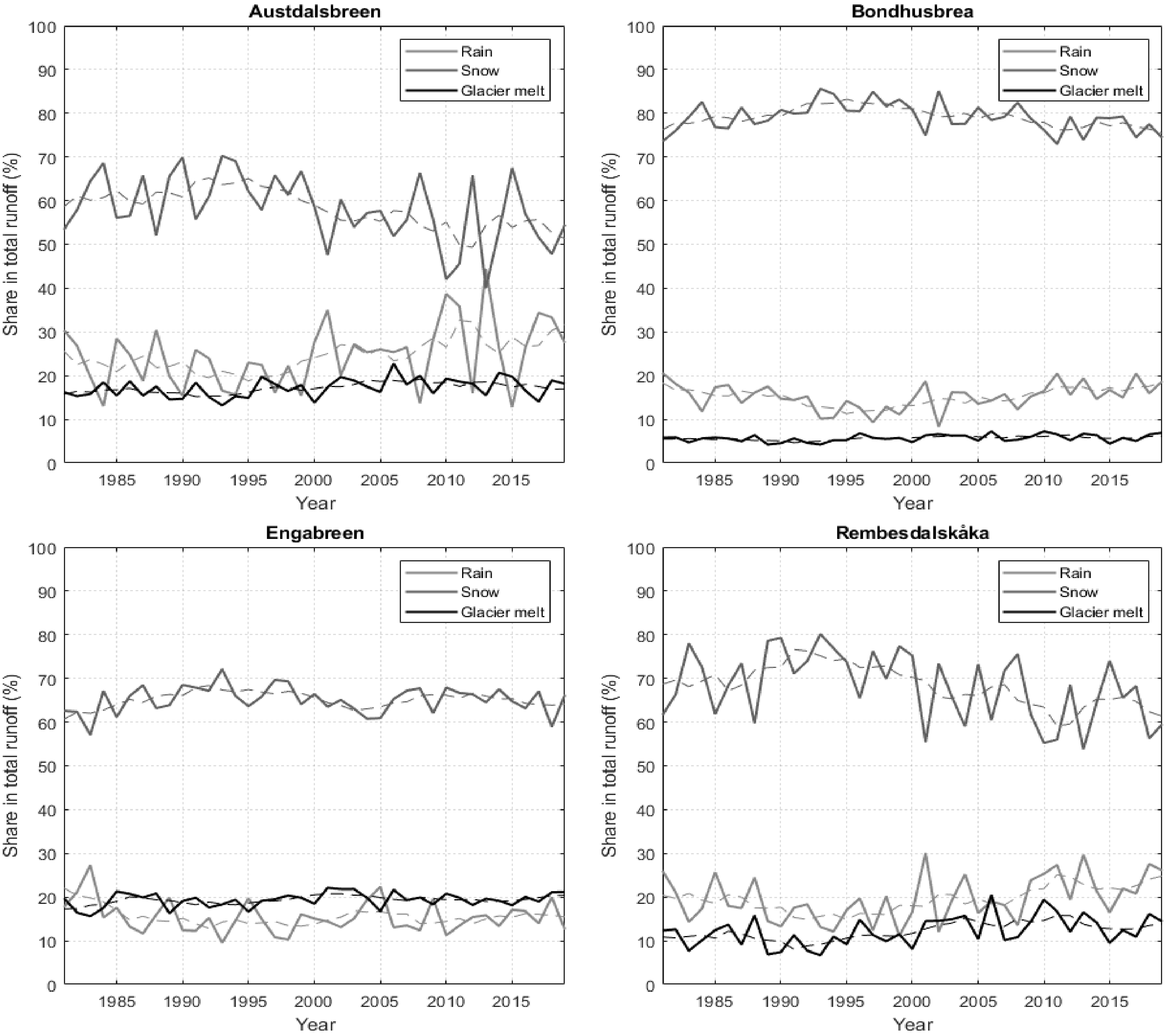


Figure 25 - Relative proportion of different runoff sources in annual total discharges. Black line represents ice melt, upper dark grey line snowmelt and rain is symbolized with the lower lighter gray lines. The dotted lines follow a 1-year moving mean.

4.4.4. Future Runoff Projections

Following the comprehensive assessment of past runoff regimes, this section is dedicated to investigate possible future runoff scenarios based on a bias-corrected version of the RCA4 regional climate model (RCM) that was selected by validating RCM performance against observational data. Future discharge is simulated by taking two greenhouse gas (GHG) concentration scenarios into consideration, the representative concentration pathway (RCP) 4.5 and 8.5 by the Intergovernmental Panel for Climate Change (IPCC).

Total discharge

Future projections (see Figure 26) indicate intense fluctuation in annual total discharge volumes at Engabreen and Bondhusbrea, whilst relatively smaller variations at Austdalsbreen and Rembesdalskåka. In general, both GHG concentration scenarios predict intensifying yearly runoff values until the middle of the 21st century with RCP 8.5 resulting in more considerable increase between 2050-2100.

At Austdalsbreen, the RCP 4.5 based model version anticipates a raise from 1.5 m/year to approximately 1.8 m/year. Regarding the RCP8.5 scheme, runoff reaches similar volumes as simulated by RCP4.5 under the same period. After 2050 both pathways predicted a reduction in volumes. However, the two simulations separate in circa 2080, when the RCP 4.5 version modeled a more modest increase than RCP 8.5. The most significant distinction between the two GHG concentration pathway simulated scenarios is that while they predict similar interannual cycles, RCP 4.5 predicts a stable runoff fluctuating around 1.5-1.7 m/month on average, whereas RCP 8.5 displays a more prominent increase in the second half of the century, frequently reaching higher than 2 m/year in 2085-2090.

Similar to Austdalsbreen, annual discharge volumes remain in the range of 1-2 m at Rembesdalskåka. Both RCP scenarios predicted increasing runoff in the next decades based. RCP 4.5 model output imply a minor increase in the long-term, with moderate declining periods. Projected runoff based on the more extreme RCP 8.5 scenario implicates comparable variations to RCP 4.5 with a slightly more outstanding increase between 2080 and 2100.

As presented in Section 4.4.2, the magnitude of runoff was highest at Bondhusbrea and Engabreean in the historic period (1981-2019). This tendency is reflected in future projection with minor differences. A Bondhusbrea, the RCP 8.5 model run predicted a peak in annual discharge between 2030-2035 and then a decrease until circa 2048. Meanwhile, the RCP 4.5 version projected a gradual, but slow increase in runoff until 2055. In the second half of the 21st

century, runoff continues to vary widely according to both sceario; thus, signaling a steady increase in the next 80 years. More distinct alterations are predicted between the two GHG scnearios after 2080 with the RCP 8.5 based projection showing a more steadily high annual runoff pattern towards the end of the 21st century.

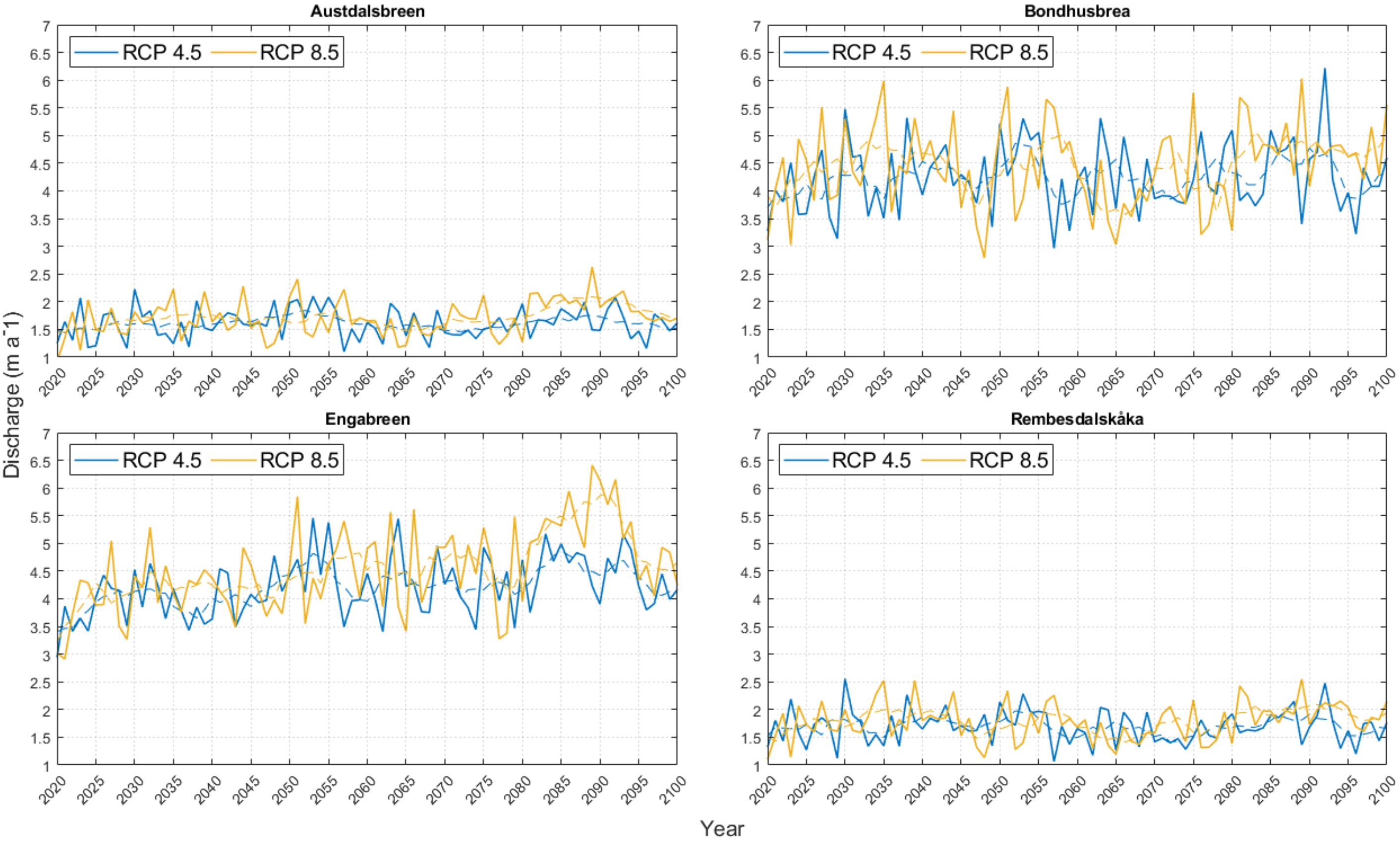


Figure 26 - Annual total runoff projections at Austdalsbreen, Bondhusbrea, Engabreen and Rembesdalskåka simulated with the RCA4 regional climate model bias-adjusted temperature and precipitation for both representative concentration pathway 4.5 and 8.5.

Contribution of runoff sources

Following the methods used to investigate the actual contribution of glaciers to the runoff on highly glacierized catchments in 1981-2019, a long-term annual source distribution analysis will be presented in this subchapter and visualized in Figure 27. Observable differences occur at every study location between RCP 4.5 and RCP 8.5 GHG concentration scenarios.

Concerning Austdalsbreen, the RCP 4.5 scenario predicted a gradually increasing share of rain and simultaneously decreasing contribution of snowmelt within the catchment boundaries. However, snowmelt is anticipated to maintain the most considerable influence on runoff regimes throughout the entire 21st century. According to the RCP 4.5 model output, the actual contribution glacier melt (snow and ice combined) to total runoff will range around 20% with a long-term, modest decline.

On the other hand, RCP 8.5 implies a shift towards rain as the dominant runoff source by the year 2060. Subsequently, the contribution of snowmelt is predicted to decrease by the end of the 21st century by roughly 15% on average. Based on the RCP 8.5 model version, the proportion of glacier melt will moderately decline over the next 80 years with a short period of higher than average annual contribution between 2040 and 2050. By the end of the 21st century, it is predicted to have approximately 4-5% less contribution to total discharge. RCP 4.5 and RCP 8.5 resulted in only minor disparities regarding the share of glacier melt by the end of the 21st century (see Figure 27).

At the same time, at Bondhusbrea, more distinct fluctuation patterns can be observed between the two GHG concentration pathways in Figure 27. The model run forced with the RCP 4.5 scenario resulted in a projection where the portion of runoff derived from snowmelt increases, whereas the share of rain reduces until 2030. After 2030, however, there is a discernible shift towards larger contributions of rain and declining ratios of snow. This tendency is sustained throughout the 21st century. During the next 80 years, glacier contribution is expected to slowly, staidly increase by roughly 4%.

On the other hand, when simulations are forced with the RCP 8.5 pathway, similar tendencies occur. However, the share of snow melt is predicted to increase until circa 2045 with rain following the opposite trend. Nevertheless, a swift decline emerges in the contribution of snow after circa 2040, which leads to a nearly 20% decrease in the contribution of snowmelt to total annual discharge by 2100. The proportion of glacier melt maintains an essentially increasing pattern on average until 2080, when it begins to marginally reduce until 2100.

At Engabreen, the two runoff scenarios projected similar variations in the contribution of various runoff sources until approximately 2055. After 2055, the RCP 4.5 based simulation then predicted glacier melt to maintain the role of primary runoff source in the second half of the century, the RCP 8.5 version anticipated a gradual switch (+10% by 2100 compared to 2020) towards rain. Both climate change scenarios result in diminishing snowmelt contribution to runoff by 2100, with the RCP 8.5 projection predicting a higher reduction. The most abrupt difference at Engabreen, compared to other locations, is the considerably higher ratio of glacier melt in the annual total discharge (see Figure 27). The most likely explanation is the extensive glacier coverage in the catchment in a geographic setting with relatively high summer temperatures. These characteristics are potentially leading to melt occurring over large portions of the glacier and a more significant contribution of glacier melt (snow and ice combined) than at the other three study basins.

The contribution of different sources in runoff is reasonably evenly distributed at Rembesdalskåka according to both the RCP 4.5 and RCP 8.5 GHG concentration scenarios. When examining the first half of the next 80 years, the RCP 4.5 based model run anticipated a stagnant decline in the share of snowmelt and glacier melt with rain demonstrating an increasing influence on runoff. This tendency remains unaltered from 2060 to 2100 and results in a change in major runoff source from snowmelt to rain from about 2080 (see Figure 27).

There are major similarities between the two GHG concentration pathway driven simulations. The RCP 8.5 version also predicted a growing impact of rain on the expense of snow melt and glacier melt. However, this version of the simulation anticipates the shift to happen substantially earlier in 2050. The direct glacier contribution at Rembesdalskåka is expected to vary stably around 20% throughout the next 80 years.

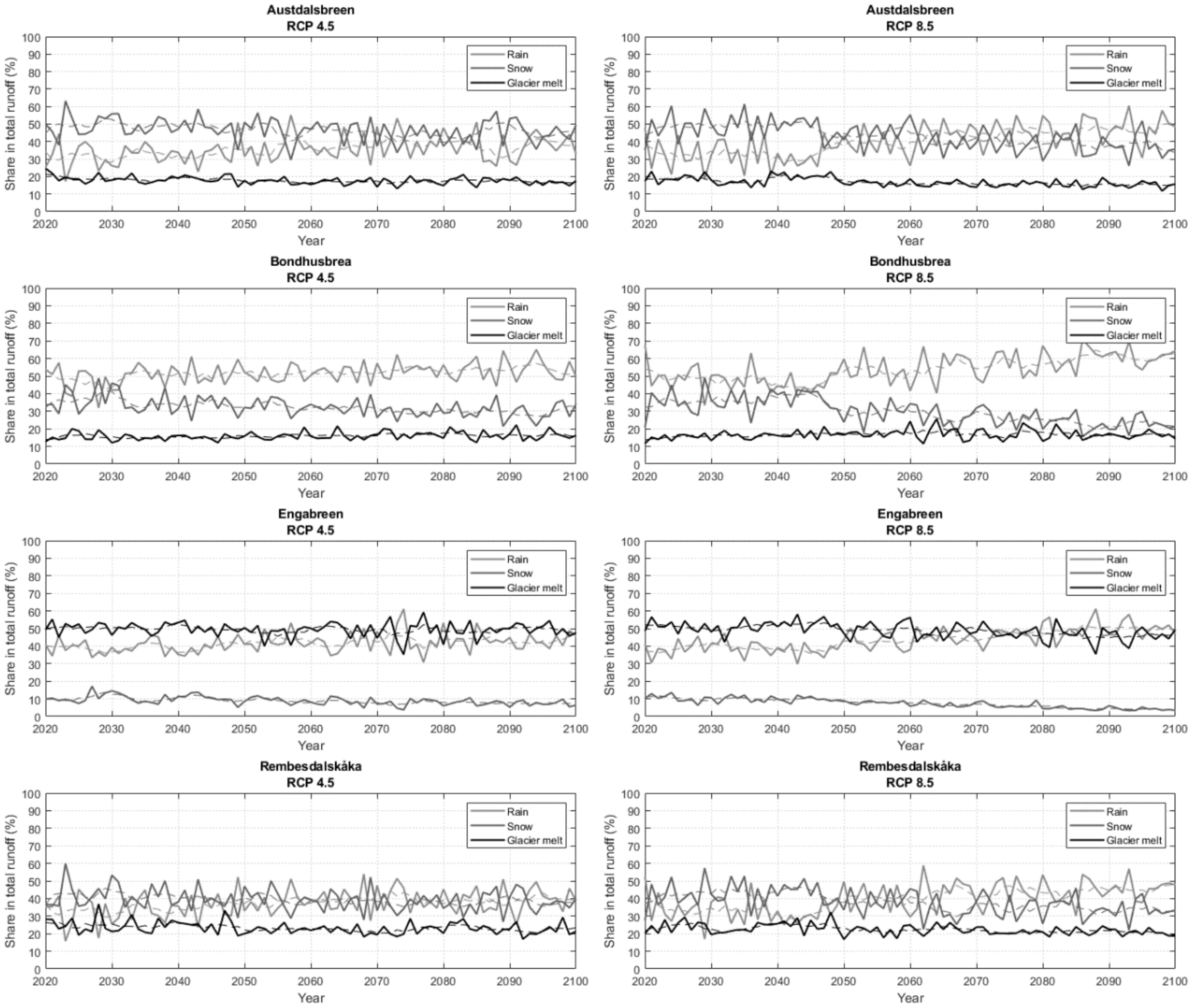


Figure 27 - Contribution of rain, snow melt in basin and glacier melt - combined snow melt and ice melt on glacier - in total annual runoff throughout the 21st century with the dashed line representing the 5-year moving average.

4.5. Results of Interviews

The human geography part of the thesis focuses on the possible implications of past, present, and future glacier-hydrology interactions on the hydropower production in Norway, as a potential socio-economic effect of changing glaciers. As previously described (see Section 3.6), the study collected vital information from experts at Statkraft through a semi-structured open-ended interview, which was sent out and collected via email.

4.5.1. The Importance of Glaciers for Hydropower Production

Most importantly, the interviews with experts unveiled helpful and noteworthy information that could not be found in research papers or showcased by merely analyzing the datasets at our disposal and simulating future run-off.

The particular interview question focusing on the issue of glacier impact on hydropower production is the following:

"What are the biggest challenges in general regarding the possible effects of reducing glacier meltwater on hydropower production in Norway? How could it affect future hydropower development?"

The study hypothesizes that glaciers will pose at least a moderate challenge to hydropower production in the 21st century. However, as summer dry periods will occur more frequently, the importance of glacier melt discharge will increase. Thus, eventually, the significant retreat or total disappearance may pose a major threat for hydropower production in the future. The respondents partly share this concern, but admit that it is hard to plan for such long periods.

Even Loe, a hydrologist at Statkraft, working closely with glaciers and hydrology in highly glacierized basins in the Jostedalsbreen region in Sogn og Fjordane county, Norway. Even L. revealed that meltwater from shrinking glaciers would increase run-off and hydropower production in the region for the foreseeable future. However, as he further explains, the second half of the century may bring a decrease in discharge, and considering that numerous power plants relying on glacier meltwater in the Jostedalsbreen region, this may lead to a reduction in energy production. On the other hand, climate change is expected to induce an increase in precipitation, as Even L. illustrates:

> For the first quite many years, the power plants in this region will receive more meltwater as the glaciers shrink. In perhaps fifty or more years the amount will

> start to decrease, causing a decrease in power production. In this region climate change seems to bring on an increase in precipitation leading to an overall increase in production in Western Norway.

Hydrologists at Statkraft's headquarter in Oslo share this perception and are not concerned about the decreasing contribution shrinking glaciers to hydropower production. The simulations ran at the Hydrology Department of Statkraft intending to predict projections of probable future discharge, and glacier contribution to run-off displays an increasing trend until around 2060 – 2070. Although, as Gaute Lappegard, Head of Hydrology, interestingly explained: This [the following 50 years] is a long period for business considerations. Who knows: Do we still have the need for hydropower in 50 years? This reply is a compelling perception, and Gaute L. continued to justify the previous statement by saying:

> I doubt there will be any further hydropower development [in Norway] since all [the] other renewable sources now have a lower investment cost than hydropower. It is more [of] a question on how long we will maintain our existing powerplants without storage capacity (run of river plants).

These comments suggest that the potential socio-economic effects that alterations in glacier-fed hydrology would pose to the Norwegian hydropower will be strongly mitigated by a shift towards more sustainable, reliable, and more cost-effective versions of renewable energy sources in the future. The response indicates that Norwegian hydropower producers may be more concerned about other competitive renewable energy sources than the potential aftereffects of climate-change-induced glacier retreat and the consequent impacts on hydrology and hydropower capacity of the country. Gaute L. further stretched this suggestion:

> (…) it is not the shrinking glaciers that some hydro[power] producers need to consider, but the competition from cheaper renewable sources [such] as wind and solar and most possible also hydrogen.

On the other hand, Sigrid Bojesen Fatnes, a hydrologist at Statkraft working in the South-West Norway region, emphasized the significant contribution of glacier meltwater during dry summer periods. Dry, precipitation scarce periods increased during summer in Norway in the 21st century, and arid periods are expected to persist and intensify in the future. Furthermore, Sigrid

B.F. highlighted the issue of changes in flow directions due to the disappearance of glaciers, which may also cause substantial problems for hydropower producers and pose natural hazards for the population. As Sigrid B.F. expressed:

> The hydropower plants and water systems in areas with glaciers are planned to optimize production for a given climate from the time of building. Most of the big plants in Norway [were built] before 1990. When the climate heats up the preconditions change. The hydrological cycle is disturbed and if the glaciers [retreat substiantially or disappear completely,] there will no longer be inflow through dry and warm summermonths. In adition melting of glaciers can reveale new lakes and the water will find new ways.

Even Loe shares the concern of diminishing glaciers' influence on watershed boundaries and on flow directions, and emphasized: Disappearing glaciers could also lead to changed watershed boundaries, increasing or decreasing the areas giving run-off to our power plants.

In conclusion, although overall energy production may not be affected by shrinking glaciers due to increasing precipitation in West-Norway in the near-future, watershed boundaries might change relatively unexpectedly, causing alterations in run-off contributing to energy production. Besides, the importance of glaciers for hydropower production will intensify with the increasingly persistent summer dry periods in Norway, when glacier melt might become the major source for energy production.

4.5.2. Adaptation to Glacier Changes

The answers for the first question were slightly unexpected, and concerns over the decreased contribution of glaciers to discharge were quickly set aside. Thus, the answers to how the limited issues generated by the retreating glaciers and climate change lost relevance somewhat. Nevertheless, it is an interesting matter, and being aware of this may contribute to discussing the findings presented in this study. The interview question addressing this subject is:

"Do Statkraft consider these potential challenges while working out strategies for future (long-term) hydropower development? If yes, how it is included in planning?"

As assumed, answers from experts all pointed towards that climate-change impacts are seriously considered when planning for future hydropower production potential. Even Loe confirming this assumption, stated:

> Statkraft has taken different climate scenarios into account when predicting future inflow. Thus, trying to make sure future projects are compatible with future climate.

Therefore, making it clear that Statkraft is taking into consideration various future climate scenarios in the process of planning production and predicting future inflow.
Moreover, experts' reactions suggest that in a world of rapid energy price changes, companies involved in hydropower production are not entirely able to plan too far into the future. Furthermore, they deem the fluctuations of prices a considerably more substantial challenge than that of the potentially reduced discharge in glacier dominated catchments. As Gaute Lappegard explicates:

> We do consider climate change and changes in discharge when we plan for future investments, but 50 years ahead is a long time, and the changes in the energy market [are] so rapid at the moment that we find it hard to look at reduced glacier volume as one of the biggest challenges.
>
> Norway has a hydro[power] production of 130-135 TWh a year. Only 4 TWh comes from power plants dominated by glaciers. To us, the changes in [the] revision of terms (Vilkårsrevisjoner) is a larger challenge. If NVE is continuing the same level of stronger restrictions, Norway will lose up to 13-15 TWh of hydropower [in] the next coming years. Compared to glaciers, this is of a bigger concern.

It is amusing to see how many immense challenges hydropower companies face. Many of them are also considered more prominent in terms of influence on the future of the Norwegian hydropower industry than the potential loss in production caused by the impacts of climate change. Nevertheless, it is clear from the answers that Statkraft keeps close tabs on climate-change-related problems and places considerable effort into monitoring the conditions of glacier dominated discharge regimes, and takes everything into account when planning for the future Norwegian hydropower production.

4.5.3. Research on Climate Change and Glaciers

The next two questions of the survey aimed at revealing the nature and extent of research Statkraft base their assumptions on. One of the objectives of the GOTHECA project is to contribute value to regional climate-change adaptation by planning for a future with vastly less glacier and meltwater and larger unpredictability and more glacier related extreme events and natural hazards. Therefore, I found it intriguing to obtain information about how companies handle this on their own and what else the project could contribute.

The questions focusing on this topic are the following:

"Is there ongoing research regarding the topic in Norway? What steps Statkraft make to learn more and be more aware of the exact extent of the potential impacts of climate change triggered glacier retreat?"

"Do Statkraft co-operate with scientific institutions to better measure and comprehend the impacts of glaciers in the future?"

As expected, Statkraft is extensively involved in R&D projects, and the research-based information facilitates precise planning for future changes. As Gaute Lappegard explains:

> Yes, we have been involved in several R&D projects where this [change in discharge in glacier dominated catchments] has been studied for more than 20 years. That is why we know that there will be an increased volume of water for the next 30-50 years. We run hydrological models forced with different GCM's, [and] we work on methods for bias correction of GCM's and downscaling algorithms to make the GCM's representative for our catchments.

Even Loe added that Statkraft is cooperating with scientific institutions in regional research of the Jostedalsbreen concerning changes of watershed boundaries:

> There is a lot of ongoing climate research. Statkraft follows this as closely as possible. Right now, we are contributing to and taking part in a project that seeks to map out potential future changes in watersheds around Jostedalsbreen.

All this is evidence that the Norwegian hydropower industry is extraordinarily well-prepared and resilient for possible alterations in the future water supply due to the effects of climate change on the cryosphere. Furthermore, the scientific findings based on the hydrological models are entirely taken into consideration when preparing for future upgrade or improvement of present hydropower plants, as Gaute L. discusses:

> We include all this [R&D] information in our decision processes when we plan for refurbishment, meaning that turbines refurbished in glacier dominated catchments will usually be replaced with larger generators to be able to handle the increased water volume expected [in] the next 30-50 years.

Besides the substantial internal R&D projects at Statkraft, the whole energy industry cooperates to better prepare for future climate-change-related challenges in joint organization, Energi Norge, representing Norwegian companies with an interest in the market of renewable energy. Research institutions and energy companies are collaborating and working together for common goals. Statkraft is no exception, as revealed by Gaute L.:

> *(...) we have a long tradition of investing in R&D. We have a long track record for working with institutions like MET, NVE, SMHI, Cicerro, Bjerknes/NORCE. Through Energi Norge, we have been involved in several projects [in] the last 20 years, aiming at understanding the consequences of climate change on our business.*

5. Discussion

In an effort to comprehensively construe the major findings presented in the results section, let us first recall the fundamental objectives of the study. The overarching theme of this thesis is to attempt to ascertain the extent to which glaciers are contributing to the runoff in highly-glacierized catchments in Norway and to determine if it will have a significant socio-economic impact by altering hydropower production in the future. Besides, the study also aims at assessing the usability of different climate datasets for modeling hydrology both in the recent past (1981-2019) and until the end of the 21st century (2020-2100). The study combines methodologies from the natural and social branches of geography, attempting to blend human and physical geographical practices to shed light on possible consequences of climate change induced variations in glaciers and consequently in hydrology on the Norwegian hydropower industry.

In the following chapter, the findings of this study will be discussed and evaluated in the light of the research questions and compared with the results of prior research in the field.

5.1. Variations in Climate, Glaciers and Runoff in the Past

5.1.1. Glacier Changes and Climatic Drivers in Norway

Climate change affects our planet in numerous and various manners. However, certain regions and habitats of the Earth are more exposed to impacts of climate change than others (Beniston et al., 2018). Mountainous areas have demonstrated one of the swiftest responses to climate change worldwide (Gobiet et al., 2014), cryosphere, the frozen elements of the surface of the planet, have exhibited the most drastic and rapid changes (Beniston et al., 2018). Glaciers in Norway are no exception. According to a recent survey by Andreassen et.al. (2020), glaciers have shrunk by an average of 10% area-wise, marking a retreat of 572 meters on average. Almost every glacier has lost mass and thinned since 1960, with substantial negative tendencies after the turn of the 21st century (Andreassen et al., 2020). Glacier mass balance, length records and frontal position maps for glaciers in this study with available data are presented in Appendix III.

For instance, glacier front records at Bondhusbrea have demonstrated stable front positions with marginal fluctuations between 1960 and 1984 (see Figure 4). In spite of having a gap in the data between 1984 and 1996, frontal measurements mark a significant advance in the 1990s. The advance in the frontal position in the 1990s is not a peculiar phenomenon observed only at Bondhusbrea. The advancing positions of glacier fronts are well documented for most glaciers across Norway (Andreassen et al., 2020). A similar tendency has been observed at Rembesdalskåka and Engabreen with negligible variations in frontal positions until the 1990s, followed by an increase in length and then a swift decline by approximately 2000 (see Appendix III).

In comparison, Austdalsbreen lacks consistent length measurements. Available mass balance records indicate a corresponding negative switch with more frequent negative annual balances from the end of the 1990s at all three glaciers with measurements in the study (see Appendix III). On the other hand, the early 1990s show prevalent positive annual balances. From the viewpoint of theoretical glaciology, the mass gained during accumulation periods at the beginning of the 1990s likely triggered the frontal advance with a slight delay.

Various studies have shown a strong correspondence between changes in glacier regimes and geometries, summer temperatures, and winter precipitation. Numerous studies have addressed mass balance sensitivity to climate factors and found that maritime glaciers in Norway are evidently more influenced by variations in winter precipitation, whilst continental glaciers are more sensitive to summer temperatures (Andreassen et al., 2005, Marzeion and Nesje, 2012, Trachsel and Nesje, 2015). Andreassen et.al. (2020) reported the highest importance of winter mass balance; thus, winter precipitation, at Engabreen and Rembesdalskåka, while Bondhusbrea is also most likely to belong to this category. In contrast, a glacier that was not involved in this study but located in the proximity of Austdalsbreen has shown a more extensive influence of temperatures and ablation (Andreassen et al., 2020). It has been demonstrated that the accumulation and ablation on glaciers, in particular the ones located in South-West Norway, are heavily impacted by variations in the North-Atlantic Oscillation (NAO) (Marzeion and Nesje, 2012, Nesje et al., 2000). The NAO is regulated by two pressure systems over the Atlantic Ocean, the Icelandic low and the Azores high. Furthermore, a period characterized by positive NAO[1] coincides with the period of consistent positive annual mass balances and mass gain between 1989 and 1995 (Andreassen et al., 2020). Other reports have suggested that winter balances of glaciers situated in Northern Norway, including Engabreen, demonstrate more robust correspondence with the fluctuations in atmospheric circulation patterns over the Arctic, modulated by the Arctic Oscillation (Rasmussen, 2007). Hence, the results of numerous earlier studies have led to a conclusion that changes in large-scale atmospheric circulations largely control glacier mass balance variations in Norway.

The significant influence of summer temperature and winter precipitation becomes conspicuous when analyzing mass balance records and length changes of the selected glaciers together with weather parameters derived from the observational climate dataset, seNorge. It is apparent that winter precipitation determines the extent of snow accumulation, and summer temperatures have a major impact on ablation during the melting season. These are the two most prominent factors that influence glacier runoff and directly relate to the large-scale circulation patterns that control local weather conditions.

In this study, two climate datasets, the seNorge observational dataset (see in Section 3.1.1), and the global climate reanalysis ERA5-Land (see in Section 3.1.2) are compared from 1981 through

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[1] Positive NAO referes to a period when pressure over the Azores is higher than over Iceland, bringing strong westerly winds that result in larger snow accumulation at higher altitudes throughout Scandinavia

2019 and used to drive simulations of the accumulation, melt and freshwater discharge, in the glacier dominated basins selected in this thesis.

5.1.2. Valley-Based Evaluation of Global versus Regional Climate Data

Mountain regions are typically marked by scarcity of weather stations that in turn leads to the lack of precise climate measurements. ERA5-Land (see in Section 3.1.2), a version of ERA5 with a larger focus on land areas, provides global climate data by combining climate models and observations from various sources. Therefore, it has provided a strong basis for numerous global warming studies and the degree to which it affects specific regions. In addition, climate reanalysis helps to understand how to improve the accuracy of climate models using data assimilation. The spatial resolution of ERA5-Land is ~ 9 km. Currently, and compared to prior versions of the ERA climate reanalysis family, it is considered sufficiently high for practical usability in climate change studies. In contrast, seNorge (see in Section 3.1.1) is a climate dataset largely relying on observations with a spatial resolution of 1 km. The results of the evaluation are presented in Section 4.3, where the performance of ERA5-Land is compared to that of seNorge and weather observations.

The evolution shows that the original ERA5-Land fails to replicate temperature and precipitation in mountainous parts of Norway. My analysis of the ERA5-Land boundary conditions points at the low spatial resolution as a possible explanation for the model fails to capture the diverse topography of steep valleys and high plateaus in southwestern and northwestern Norway. The large deviations between the global ASTER digital elevation model (30-meter resolution) and the interpolated orography data of ERA5-Land are evident (see Figure 28). Naturally, it causes a possible explanation for the model failure, such as found in the vicinity of Austdalsbreen. ERA5-Land performs considerably better in the vicinity of, for instance, Rembesdalskåka, where most of the weather stations are located on a plateau with less diverse terrain; however, it is still outperformed significantly by seNorge. Its nature can explain the better performance of seNorge. seNorge is based on observations measured at weather stations; thus, seNorge will always capture weather conditions better than ERA5-Land at weather station locations.

Due to the recent release of ERA5-Land in 2019, momentarily, there is a lack of research aiming at assessing the performance of the climate reanalysis in different parts of the planet, and this study is, therefore, a direct contribution to such assessment.

5.1.3. Tackling Low Resolution Climate Data

Compared to the raw ERA5-Land dataset, the evaluation of the downscaled temperature series demonstrates a potential to improve its products significantly at most of the study locations. Downscaling of ERA5-Land is presented in Section 4.4., where downscaled ERA5-Land is compared to original ERA5-Land and observed values from weather stations to determine if downscaling and adjusting for local topographic conditions will improve performance.

According to the findings, the specific type of downscaling applied in this study (see Section 3.4) brings the most considerable improvements at the two ends of the palette in terms of elevation, mostly because the original ERA5-Land seemingly performs worst at these respective altitudes. However, the altitudes original ERA5-Land performs worse can be of huge significance in studies aiming to address runoff since they involve substantial portions of the accumulation and ablation zones.

The degree of improvement is clearly dependent on the temperature or precipitation lapse rates used during the downscaling process. In this study, slope lapse rates were derived using different approaches (see Sections 3.4.1. and 4.3.1.) and compared. Slope lapse rates are known to fluctuate substantially both spatially and temporally; hence the use of a static lapse rate is unrealistic. Naturally, the most outstanding improvement was achieved by monthly, seasonally varying slope lapse rates. In spite of improving ERA5-Land, the downscaling and orographic adjustment did not make ERA5-Land perform on the level of seNorge.

In conclusion, applying a specific downscaling method improved ERA5-Land considerably (see Sections 4.3.2. and 4.3.3.), and despite not matching the accuracy of seNorge, shows great potential to enhance performance and usability in regions where observational data is scarce.

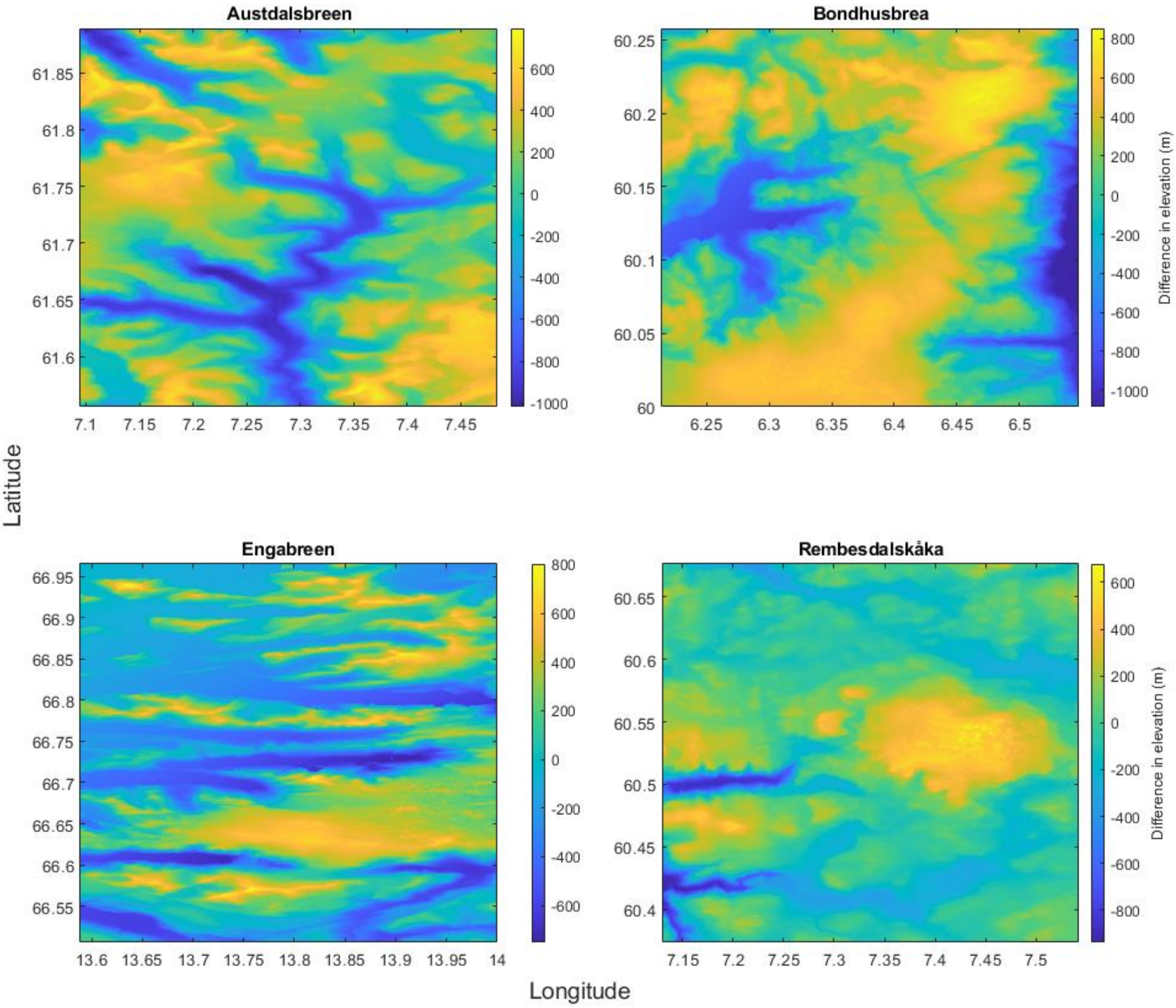


Figure 28 - Differences in elevation between the global ASTER digital elevation model and the elevation data of ERA5-Land. Axis indicates geographic coordinates.

5.1.4. Reconstructions of the Historical Runoff

The evaluation of the direct impact of glaciers on the overall runoff in the studied basins was based on the PDD model output that used seNorge temperature and precipitation as input since it proved to perform better for capturing temperature and precipitation locally than ERA5-Land. Glaciers are well known for their role as fresh-water reservoirs, and the influence of glaciers can be immense in certain parts of the world, especially during summer, where glacier melt discharge compensates for the lack of summer precipitation. In this section, the variations in annual discharge, seasonal distribution of runoff, and the contribution of different sources in the runoff as reconstructed by the PDD model (see Section 3.5) are evaluated and discussed to shed light on runoff fluctuations and the importance of glaciers in highly glacierized basins in Norway in the past 40 years (1981-2019).

Discharge modeling revealed a general increase in runoff between 1981 and 2019 at every catchment addressed in this study. The most substantial increase was observed in the northernmost location, at Engabreen. Temporally, the higher annual discharge values of the 1990s stand out. This surge in total streamflow aligns well with the period of mass surplus and glacier advance during the 1990s (Winkler et al., 2009, Xu et al., 2012, Engelhardt et al., 2015, Kjøllmoen et al., 2019, Andreassen et al., 2020). Examining climate patterns, a significant rise in winter precipitation can be observed between the 1990 and 1995 period, which shown to have led to more robust accumulation. Summer temperatures remained stable during the same period with a considerably warmer short period at the end of the decade (the 1990s). This warm year matches a peak in the yearly total runoff in every catchment. After the turn of the 21st century, an evident decrease in mean long-term runoff began at Austdalsbreen and Rembesdalskåka, as opposed to relatively steady streamflow in the catchment of Bondhusbrea.

In contrast, discharge at Engabreen peaked between 2000 and 2010 with a rapid reduction afterward. In most recent years, since 2012, discharge at Austdalsbreen, Rembesdalskåka, and Bondhusbrea started to increase again, whereas streamflow continued to slowly decrease until 2019. The decrease at Engabreen coincides with a period of lower than average winter and summer precipitation but relatively high summer temperatures, suggesting an essential influence of precipitation on the yearly runoff cycle.

The PDD model results indicate that the glacier melt contribution increased at every site to a varying extent in 2001-2019 relative to 1981-2000. The most apparent increase (+ 3-5 %) is reconstructed for Austdalsbreen and Rembesdalskåka, whereas glacier melt contribution remained stable at Engabreen (~ 20 %) and Bondhusbrea (~ 8 %) with only minor fluctuations over the past 40 years. The spatial evaluation of runoff patterns also suggest a growing influence of glacier melt (combined snow and ice melt) in the second half of the last 40 years (2001-2019) compared to 1981-2000 with the most prominent increase at Austdalsbreen and Rembdesdalskåka (see Sections 4.4.2 and 4.4.3).

To date, there are relatively few studies focusing specifically on quantifying the contribution of glacier melt to discharge in Norway. Prior research showed similar results for Nigardsbreen, Storbreen, and Ålfotbreen to those presented in this study. Despite being located approximately 670 km south of Engabreen, Ålfotbreen - a maritime glacier near the west coast of Norway - showed similar patterns of annual discharge variations (Engelhardt et al., 2014). Furthermore, it has been observed that temporal fluctuations in annual discharge sums decreased with increasing climate continentality (Engelhardt et al., 2014), which matches the results of the PDD model in this study. However, the decrease that was modeled for runoff in this study at Austdalsbreen and Rembesdalskåka between 2000 and 2012 is absent in modeled discharge records reported by Engelhardt et.al. (2014) among the three glaciers addressed by their research.

Nevertheless, despite focusing on different study basins, their findings support the overall increase in annual discharge sums between 1981 and the end of their (Engelhardt et al., 2014) study period, which is 2012. Moreover, there is a discrepancy between the ratio of contributing sources reported by Engelhardt et.al. (2014) and found in this study. Whereas the results of the PDD model suggest a general increase in the contribution of rain and a slighter increase in the share of glacier melt, Engelhardt et.al. (2014) reported relatively stable trends and tendencies of the proportion of rain the in total runoff and a more considerable increase in the contribution of glacier melt. Nevertheless, increase in glacier melt contribution with growing continentality was observed among the studied glaciers in this thesis, which aligns well with the findings of Engelhardt et.al. (2014) for the three addressed glaciers in their study.

5.1.5. Impacts of Simplifications in the Melt Model

Several modeling approaches exist for simulating runoff regimes. In this study, a positive degree-day model (PDD) was applied to reconstruct past runoff variations and project future runoff scenarios in the four selected study basins. However, several factors influence model performance, such as the input data and specific parameters. Compared to more advanced approaches, as discussed at the end of the previous section, the PDD model generally performs sufficiently, but discrepancies occurred in some cases, which might be caused by simplifying specific real-life processes in the modeling approach used in this study. The impacts of using this particular PDD model approach will be discussed in this section.

Despite the imperfect skill of the downscaled ERA5-Land compared to seNorge, both downscaled datasets were used as input in the PDD model to assess how using different datasets alters model reconstructions. In order to ensure that the PDD model results are sufficiently accurate, they were validated against mass balance measurements and runoff observations, where such data were available. Moreover, two statistical tests (see Section 3.5.3) were used to quantify model performance.

Due to the unavailability of sufficiently long observational records, the PDD model outputs were validated against runoff measurements at only Engabreen. The model captured seasonal and long-term discharge trends reasonably well, regardless of the input data. The major difference is in how well the simulations replicate maximum and minimum streamflow. In conclusion, ERA5-Land is an adequate option for regions with a lack of observational data; however, depending on the complexity of the terrain, adjustments for deviations in elevation due to coarse spatial resolution are recommended where possible. Sufficiently long mass-balance measurements were available at three glacier. The coefficient of variation (CV) statistical test revealed that the seNorge driven PDD model output reconstructed past seasonal mass-balance variations better than the ERA5-Land version, which is supported by consistently lower CV values suggesting more precise results for seNorge.

The model validation revealed that the PDD model run driven by downscaled seNorge data replicated both runoff and mass balance measurements most precisely. Hence, the seNorge data set was eventually selected to force the PDD model over the past 40 years; and thus, to reconstruct the historical runoff evolution. Therefore, these PDD model outputs will be discussed in more detail from now on. For a full representation of the PDD model validation, see Section 4.4.1.

The modeled monthly discharge demonstrated a good agreement with observed values in the reference period of 1981-1993 (precise validation of model performance was not feasible after 1993 due to biases in data following the opening of the subglacial tunnel for hydropower purposes). When comparing with similar studies using different approaches (Engelhardt et al., 2014), the PDD model managed to capture runoff variations relatively well, which is supported by a Nash-Sutcliffe coefficient of 0.85.

There occurred, however, larger deviations when comparing with mass balance measurements. Considering spatial deviations in model performance for restructuring mass balance records, the PDD model evidently captured seasonal mass balance variations best at Engabreen. This is most likely due to the choice of model parameters, such as snow and ice melt factors, which in this study were obtained from the literature. Melt factors of snow and ice were estimated most recently at Engabreen (Andreassen et al., 2006), which is likely more accurate for this reason. This may lead to a better model performance at Engabreen compared to other study sites. Temporally, modeled summer and winter mass balance matches measurements best before 2000 with larger deviations between 2000-2019. Still, taking into account that more advanced discharge models resulted only in marginally better agreement with measurements when studying other glaciers (Engelhardt et al., 2014), the performance of the PDD model for simulating runoff variations is deemed to be acceptable.

Do these inferences mean that we can trust the model? There are numerous challenges when simulating runoff. In this particular case, PDD model parameters, such as degree-day factors for ice and snow, the standard deviation of temperature, and the snow/ rain threshold temperature, play a vital role in the model's ability to reproduce the actual discharge in strongly glacierized catchments. For instance, the model applies a simple static temperature threshold to distinguish between solid and liquid precipitation, which does not match real-life physical processes properly and may significantly influence the modeled contribution of snowmelt and rain to total runoff. A temperature-based method with a transitional range, where snow and rain occur as a mixture – not as either rain or snow in precipitation (Kienzle, 2008) - could possibly further improve the accuracy of the model.

Besides, the PDD model operates with a static standard deviation of temperature, whereas it is a climatic factor known to vary both spatially and temporally, even on the valley level (Rogozhina and Rau, 2014). In addition, the snow and ice melt factors are also known to vary considerably spatially. Melt factors for snow and ice used in the PDD model were adapted from previous research, addressing only one glacier, Engabreen, covered in this study. Therefore, the 'closest location with available melt factors' may significantly decrease the model accuracy due to inherent spatial variations in melt factors.

Potential additional improvements for the PDD model involve the incorporation of a retention component (Janssens and Huybrechts, 2000) accounting for glacier decrease and area loss, the inclusion of more precise melt factors for snow and ice, an implementation of a spatially and temporally varying standard deviation of temperature and a more advance rain/snow separating scheme. Several of these possible improvements may be significant for the more accurate implementation of future runoff projections.

5.1.6. Drivers of Runoff Variations in Norway

The actual share of glacier melt in total runoff depends on several factors. One hugely influential determinant is the topographic aspect reflecting the glacier coverage in the basins. Glacier coverage is highest at Engabreen (~ 70%), while it is significantly lower at other locations, namely 28% at Austdalsbreen, 40% at Bondhusbrea, and 42% at Rembesdalskåka. Moreover, the mean, maximum, and minimum altitudes of the glacier may also have a major impact on runoff by influencing the extent of the ablation zone.

Austdalsbreen lies within the range between 1227 m.a.s.l. and 1755 m.a.s.l. with the majority of the glacier situated between 1550 m.a.s.l. and 1755 m.a.s.l. High average altitude combined with low annual mean temperatures implies that ablation often occurs on a relatively small portion of the glacier. However, when summer temperatures reach a certain threshold, the equilibrium line altitude rises, and ablation affects significant or the entire area of the glacier surface. This phenomenon happened more frequently after 2000, leading to a growing influence of the glacier on total runoff in the streamflow basin. High elevations, the glacier location on the east-facing side of the icecap, and low winter precipitation rates come together to substantially lower discharge sums at Austdalsbreen compared to, for instance, Bondhusbrea exhibits almost the same degree of glacier coverage in the catchment. The low rates of winter precipitation also lead to earlier exposure of glacier ice during the melting season (Engelhardt et al., 2014), providing an additional explanation for the larger contribution of ice melt.

In contrast, Bondhusbrea is placed between 560 m.a.s.l. and 1633 m.a.s.l., with the majority of the glacier area spread above 1500 m.a.s.l. Bondhusbrea is facing west and located closer to the ocean, thus receiving considerably more precipitation. Summer temperatures at Bondhusbrea rose stably after 2000, which likely led to an expansion of the ablation zone and an increase in the total contribution of glacier melt. However, as the spatial analysis in Section 4.3 suggests, the increased impact of glacier melt in 2001-2019 is less apparent since it is balanced by rain and snowmelt in the non-glaciated, a.k.a. larger, portion of the basin.

Similarly to Austdalsbreen, the majority of the glacier area of Rembesdalskåka lies above 1600 m.a.s.l., with a minimum altitude of 1113 m.a.s.l., while the catchment of Rembesdalskåka is also the farthest from the coast among the four included study sites. This results in a very similar runoff pattern to that of Austdalsbreen, with a substantial increase in the share of glacier melt (snow and ice melt combined) between 2001 and 2019 compared to the prior 20-year period. At the same time, the proportion of rain in total discharge also increased more substantially at Austdalsbreen and Rembesdalskåka compared to Bondhusbrea or Engabreen.

Most of Engabreen is located between altitudes of 1200 and 1450 m.a.s.l., with a minimum elevation of 73 m.a.s.l. and in the proximity of the coast, which results in high winter precipitation rates. Despite the fact that Engabreen is located several hundred kilometers to the north of the other glaciers included in the study, summer temperatures are similar to those demonstrated at Austdalsbreen. The vicinity of the ocean and plenty of winter precipitation combined with the relatively low average altitude of the glacier and high glacier coverage prompt very high discharge rates relative to the other basins.

According to Engelhardt et.al. (2014), however, climate continentality carries a more extensive influence on long-term runoff patterns than the size of the basin, glacier coverage (Engelhardt et al., 2014) or the average elevation of the glacier area and; thus, the extent of the ablation zone. Discharge regimes of maritime glacierized basins are often more sensitive to precipitation, while the impact of summer temperature grows with increasing climate continentality(Engelhardt et al., 2014). The phenomenon of the more substantial impact of the distance from the coast on runoff regimes may explain that despite being the smallest catchment and its location on considerably higher latitudes among the studied basins, Engabreen exhibits significantly higher annual discharge values compared to the two glaciers with larger catchment size and more southernly locations but farther from the ocean.

Moreover, a correlation between temperature and discharge usually increases with larger glacier coverage (Chen and Ohmura, 1990), which in this study mostly relevant for Engabreen, which has the highest percentage of glacier cover in the basin among other the study catchments. However, there is no evidence for such a relationship in Norway, where previous research has suggested a more significant influence of continentality and distance from the coast than of the ratio of area covered with glaciers in the catchment (Engelhardt et al., 2015).

Regarding the glaciers in this study, Engabreen is a maritime glacier and thus, despite it is being located at considerably higher latitudes compared to other study locations, likely affected more by fluctuations in annual precipitation than temperature. Analyzing reconstructed runoff variations and corresponding summer temperatures and winter precipitation, it is evident that runoff patterns are better aligned with fluctuations in precipitation than in temperature; thus, supporting this theory. However, at this latitude, higher solar radiation during the midnight sun period also affects summer discharge to a larger extent than Southern Norway (Engelhardt et al., 2015). Bondhusbrea indicates similar weather conditions to Engabreen, but it demonstrated slightly less variation in the annual discharge pattern during the last 40 years. Austdalsbreen and Rembesdalskåka exhibit characteristics of glaciers with more pronounced climate continentality, such as higher glacier melt contribution to total runoff and substantially lower total annual precipitation. In addition, past runoff variations at Austdalsbreen and Rembesdalskåka match summer temperature fluctuations better than winter precipitation; hence, fitting into earlier research suggesting an increasing impact of temperature with growing climate continentality (Engelhardt et al., 2014).

5.2. Future projections

5.2.1. Catchment-Level Evaluation of Future Climate Projections

There will always be uncertainties when creating projections into the future. In this study, an evaluation of temperature and precipitation time series obtained from the regional climate model (RCM) RCA4 and its three bias-corrected versions was performed by validating them against weather station (WS) measurements and comparing with the observational dataset, seNorge, and the global climate reanalysis ERA5-Land in the reference period of 1979-2019. The assessment was quantified by implementing a root mean square error (RMSE) test (see Section 3.3). The results of the RCM performance assessment are presented comprehensively in Section 4.2.

The assessment revealed that the original RCM output captured both temperature and precipitation patterns poorly. However, the bias-correction methods enabled an improved model performance to a varying degree, resulting in a relatively good performance of the bias-adjusted versions over the reference period. Due to being based on observations, seNorge outperformed every other dataset substantially. However, the bias-corrections have enhanced the RCM's ability to replicate observations to such a degree that it often matched observations better than ERA5-Land.

When it comes to precipitation, climate products seemingly struggle to capture the observed data competently. Earlier studies, however, revealed that the gridded seNorge precipitation dataset adequately reproduces precipitation in high-mountain regions of Norway and provides a solid basis for studying glaciers (Engelhardt et al., 2012). Comparing errors produced by RCM outputs against precipitation observations indicates generally more unsatisfactory performance for simulating precipitation compared to seNorge or ERA5-Land with approximately three times higher root mean square error (RMSE) values on average relative to seNorge (see Table 6). This result implies a considerably lower reliability of climate models for simulating precipitation when compared to datasets involving or entirely built upon observations, thus, providing a significant limitation for the quality of future projections.

Several studies aimed to assess RCM performance in Scandinavia in the past. Findings show dissimilar results for different GCM-RCM combinations. In general, climate models demonstrate exemplary skills in capturing annual temperature cycles, but no RCM performed similarly well in modeling either absolute temperature or precipitation in Sweden and Norway (Landgren et al., 2014). In addition, it has been established that climate variables in the complex topographic environment must be modeled with higher spatial resolution and adjustments for altitude

(Heikkilä et al., 2011, Güttler et al., 2015), since steep topographic gradients influence precipitation rates (Dyrrdal et al., 2018). As presented in Section 4.3, downscaling and orographic correction supported by a high-resolution DEM has the potential to improve the performance of the RCM in capturing temperature and precipitation more precisely, albeit with considerable spatial and temporal variations, which bears a substantial effect on estimating glacier accumulation and melt. Enhancing spatial resolution of RCMs has given good results before: Kendon et al. (2012), for instance, compared 12 km and 1.5 km resolution RCMs in the United Kingdom, and the results revealed a much more realistic spatial and temporal representation of precipitation by the 1.5 km resolution RCM.

Prior research focusing on an earlier version of the RCM used in this thesis revealed that large-scale atmospheric circulation, sea surface temperature, and sea-ice cover derived from the driving global circulation model (GCM) likely causes the major biases in RCM runs over Scandinavia (Kjellström et al., 2011). Some of the biases were reportedly mitigated in the newer, improved versions of the RCM (Samuelsson et al., 2011). Findings of previous studies also highlight the need for bias-correction of RCM outputs for local scale applications (Landgren et al., 2014, Dyrrdal et al., 2018). The use of bias-adjusted RCM outputs in this study is shown to enhance the model precision to a reasonable degree, such as presented in (see Table 5). In addition, there is an ongoing effort to improve RCM model performances within the CORDEX climate model community (Jacob et al., 2020).

5.2.2. Future Runoff Regime Projections

There will always be uncertainties when creating projections into the future. In this study, an evaluation of temperature and precipitation time series obtained from the regional climate model (RCM) RCA4 and its three bias-corrected versions was performed by validating them against weather station (WS) measurements and comparing with the observational dataset, seNorge, and the global climate reanalysis ERA5-Land in the reference period of 1979-2019. The assessment was carried out using a root mean square error (RMSE) test (see Section 3.3). The results of the RCM performance assessment are presented comprehensively in Section 4.2 and discussed in the following paragraphs.

The assessment revealed that the original RCM output captured both temperature and precipitation patterns poorly. However, the bias-correction methods enabled an improved model performance to a varying degree, resulting in a relatively good performance of the bias-adjusted versions over the reference period. Due to the fact that seNorge is based on observations, it naturally and substantially outperformed all model-derived datasets. However, the bias-corrections have enhanced the RCM’s ability to replicate observations to such a degree that it often matched observations better than the climate reanalysis (ERA5-Land). Keeping in mind that climate reanalyses are based on the model assimilation of observational data, bias correction methods have featured as powerful tools for improvements of unconstrained climate model outputs on local to regional scales, at least in the case of near-surface air temperatures.

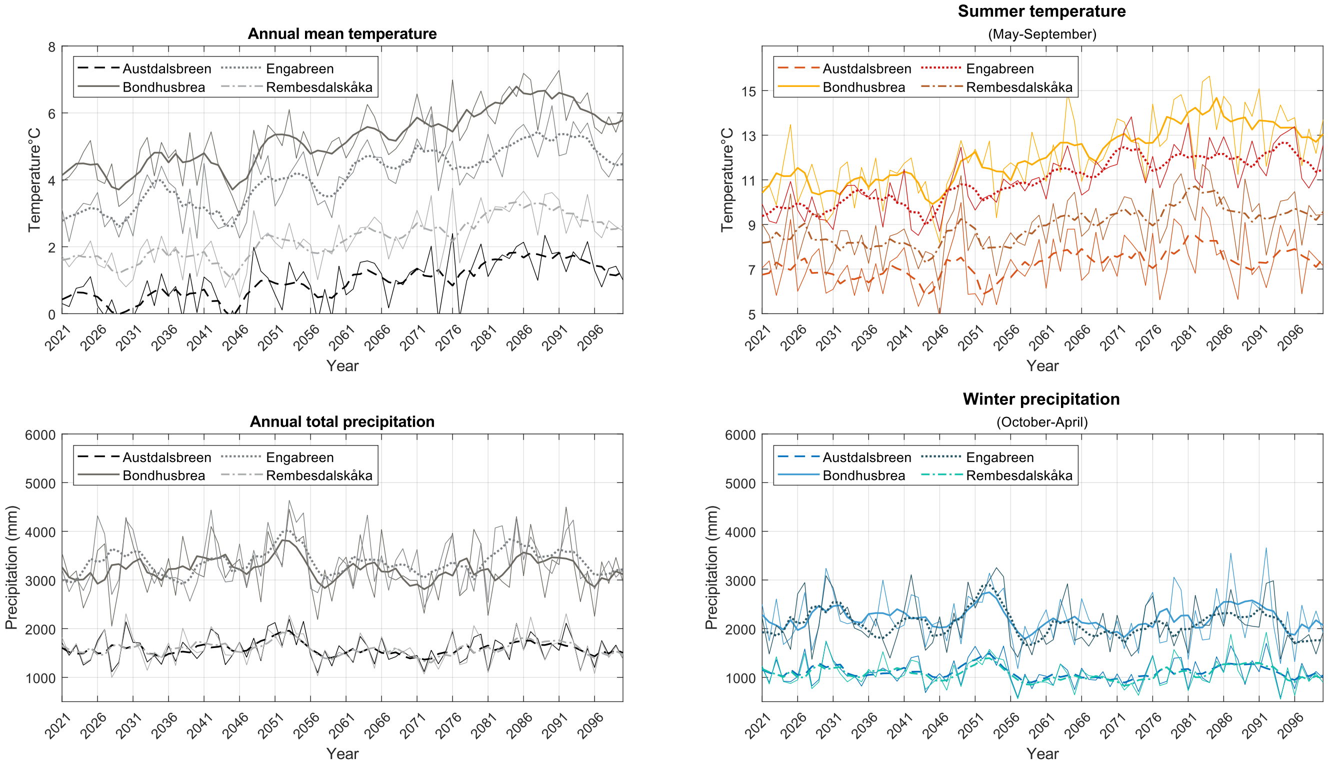
When it comes to precipitation, climate products seemingly struggle to capture the observed data competently. Earlier studies, however, revealed that the gridded seNorge precipitation dataset adequately reproduced precipitation in high-mountain regions of Norway and provided a solid basis for studying glaciers (Engelhardt et al., 2012). Comparison of RCM outputs with precipitation observations indicates a generally unsatisfactory performance compared to both seNorge and ERA5-Land, with approximately three times higher RMSE values on average than found for seNorge (see Table 6). This result implies a considerably lower reliability of climate models for simulating precipitation when compared to datasets involving or entirely built upon observations, thus casting doubt on the quality of future projections.

Several studies aimed to assess RCM performance across Scandinavia in the past. Their findings show dissimilar results for different general circulation model (GCM)-RCM combinations. In general, climate models demonstrated exemplary skills in capturing annual temperature cycles, but no RCM performed similarly well in modeling either absolute temperature or precipitation in Sweden and Norway (Landgren et al., 2014). In addition, it has been established that in the complex topographic environment, climate variables must be modeled with higher spatial resolution and adjustments for altitude (Heikkilä et al., 2011, Güttler et al., 2015), due to strong influence of steep topographic gradients on precipitation rates (Dyrrdal et al., 2018). As presented in Section 4.3, downscaling and orographic correction supported by a high-resolution DEM have the potential to improve the performance of RCMs in capturing temperature and precipitation more precisely, albeit with considerable spatial and temporal variations and thus substantial effects on glacier accumulation and melt. Enhancing spatial resolution of RCMs has given good results before: Kendon et al. (2012), for instance, compared 12 km and 1.5 km resolution RCMs in the United Kingdom and revealed a much more realistic spatial and temporal representation of precipitation by the 1.5 km resolution RCM.

Prior research focusing on an earlier version of the RCM used in this thesis revealed that boundary conditions obtained from a GCM (e.g., large-scale atmospheric circulation patterns, sea surface temperature and sea-ice cover) GCM likely caused major biases in RCM runs over

Scandinavia (Kjellström et al., 2011). Some of the biases were reportedly mitigated by the newer, improved versions of the RCM (Samuelsson et al., 2011). Findings of previous studies also highlighted the need for bias-correction of RCM outputs for local scale applications (Landgren et al., 2014, Dyrrdal et al., 2018). The use of bias-adjusted RCM outputs in this study is shown to enhance the model precision to a reasonable degree, such as presented in Table 5. In addition, there is an ongoing effort to further improve RCM model physics and performance within the CORDEX climate model community (Jacob et al., 2020).

RCP 4.5 GHG concentration scenario



RCP 8.5 GHG concentration scenario

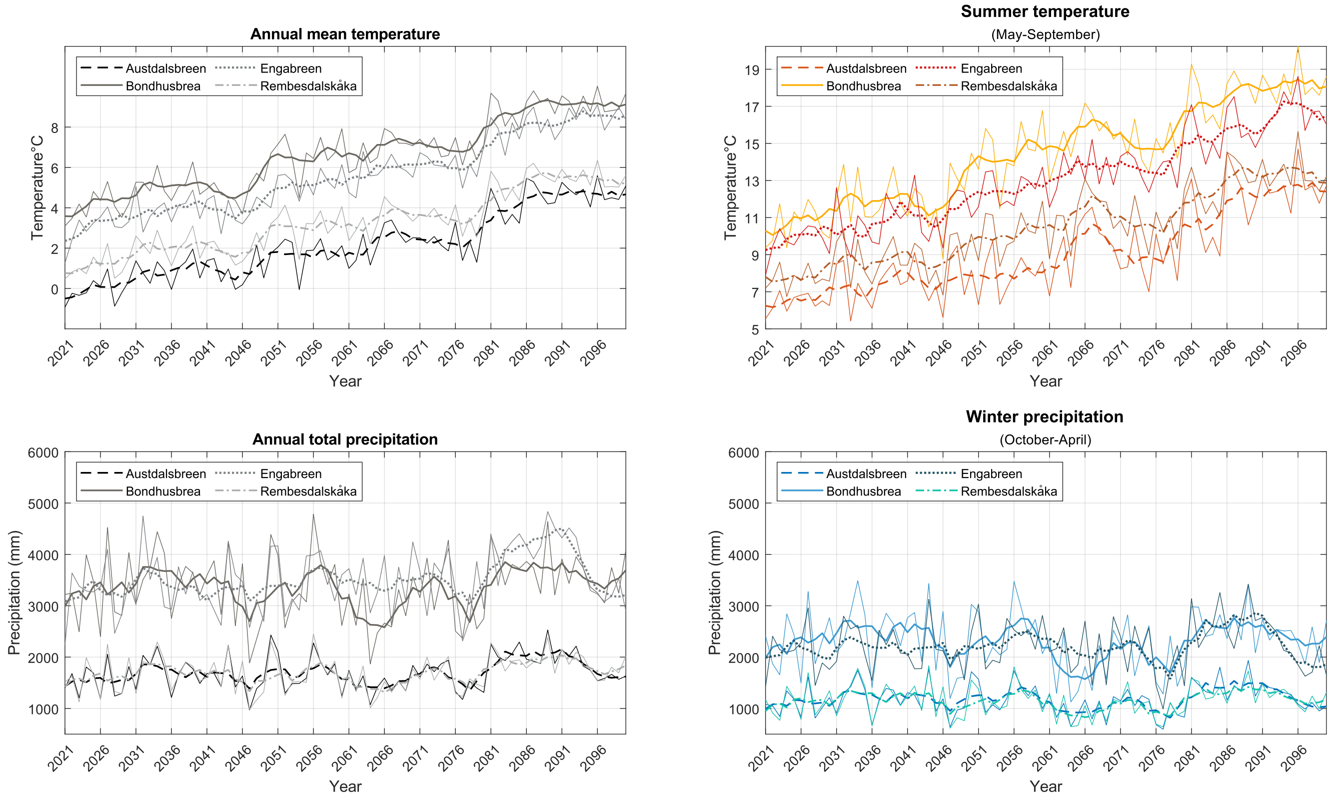


Figure 29 - Projected future seasonal and annual mean temperature and total precipitation in the four study basins with the 5 year moving average being showed too. The graph is in svg. format, therefore it will remain high-quality when zooming in.

5.2.3. Repercussions for the Hydropower Industry

Norway has, for a long time, been generating the majority of electricity through hydropower, with over 95% of the consumed electricity today produced by hydropower plants. Therefore, both quantitative and qualitative assessments of changes in discharge are essential for providing the country with energy. This thesis has assembled a range of expert opinions based on interviews with employees of Statkraft that evaluate probable consequences of glacier retreat and altered runoff regimes due to climate change for future hydropower production .

Since the analyzed glacierized catchments have been selected to represent both south-north and west-east orientations, they are likely to capture more general trends applicable in a larger-scale context of Norway. As described in the previous section, total annual runoff is expected to remain stable or rise, with larger increases expected close to the coast. Most importantly for the hydropower industry, in spite of increasing temperatures and retreating glaciers, there is no indication of diminishing runoff until the end of the 21st century. It is found that most significant changes will occur in the seasonal distribution of runoff, with more streamflow occurring earlier in the year (Lappegard et al., 2006), and that shares of contributing sources will alter, marking an increased contribution of rain and decreased importance of snow (Hanssen-Bauer et al., 2017). Given all the above considerations, a question arises: How will these changes will affect the hydropower industry in Norway?

According to the interviews (see Section 4.5) carried out within the framework of this study, there is no concern regarding glacier recession among the Norwegian hydropower industry actors. According to experts, the impact of retreating glaciers is of minor significance to the industry, and there are other more urgent and influential issues that concern hydropower companies, such as a better cost-efficiency of other renewable energy sources and fluctuating market prices.

The potential for further expansion of the current hydropower plant system was also discussed in the interviews. Experts suggested that the most likely scenario was to maintain current powerplants and consider the effectiveness of hydropower stations without storage capacity (installed on rivers without reservoirs). Statkraft, the largest operator in the market, has an internal department for determining probable future runoff scenarios in the extensive network of basins utilized for hydropower purposes. Their simulations support the scenario of increasing streamflow for the coming decades, while the company is monitoring the situation constantly in collaboration with research institutes and other operators of the industry. Hence, Statkraft is capable of adapting swiftly to potential seasonal alterations that climate change may cause by adjusting reservoir levels and energy production accordingly. A probable rise in the spring and winter streamflow may even be beneficial, since it strongly coincides with a period of generally higher electricity consumption (Lappegard et al., 2006) during the heating season in Norway. However, one respondent highlighted the increasing importance of glacier meltwater during unusually arid periods, when discharge from glaciers is the primary source of runoff in Norway. An intensification and higher frequency of dry periods in the future will highlight the prominence of glaciers and the consequences of their substantial reduction or complete disappearance for hydropower production.

Among other possible effects of melting glaciers and changing streamflow regimes, sudden flooding and glacier lake outburst floods are the primary concerns. Such events are not uncommon in Norway (Jackson and Ragulina, 2014). However, due to the comprehensive systems of dams and tunnels that facilitate the water supply of hydropower plants, these events can be largely mitigated by controlling water levels in reservoirs. Despite the recent sporadic cases of glacier-related damages, this is an issue that hydropower companies, together with institutions, such as NVE, are keen to comprehend as precisely as possible to prevent hazardous events in the future.

The general conclusion is that the direct impact of retreating glaciers will cause little concern for hydropower production and population in Norway by the end of the 21st century. Nevertheless, continuous research is needed to monitor changes and understand occurrence of extreme events, such as long dry periods when glaciers are the primary source of runoff, and adjust water management practices accordingly.

5.3. Limitations in Future Projections and Steps for Improvement

Every research endeavour starts with simple solutions and necessary approximations, which are then followed by a more detailed development in the field. During the implementation of the project, several limitations to the assessment approach have been revealed, including the choice of the climate forcing for the future projections and the simplified treatment of the surface mass balance and glacier dynamics. However, the results obtained here can be considered as a robust first-order approximation for the future, more process-based assessment studies.

Choice of the climate forcing: Following a thorough literature review and recommendations from experts, GCM-RCM simulations from the EURO-CORDEX initiative were selected based on their previously demonstrated good performances in capturing temperature and precipitation patterns across Scandinavia. The original and bias-adjusted RCM outputs were first assessed against seNorge and observations. The best performing version of the model was then applied to simulate future runoff. Despite the improvements shown by the bias-adjustment methods, the use of only one GCM-RCM combination likely carries limitations, when it comes to predicting future temperature and precipitation regimes, even though it is considered as the most representatve regional model for the region. Therefore, the expansion of the number GCM used as boundary conditions in the RCM would present a probable improvement and more reliable future projections.

Besides the data used as climate forcing in the model, the PDD model itself contains uncertainties due to poorly constrained model parameters and the lack of proper treatment of atmospheric physics and energy balance in the boundary layer.

For example, degree-day factors and daily temperature standard deviation applied in the PDD model are poorly constrained for the regional applications, and the adaptation of temporally and spatially varying model parameters, for instance, would likely improve the model performance (Rogozhina and Rau, 2014, He et al., 2014). Additionally, studying the impacts of glaciers on runoff in the long-term requires taking glacier dynamics and retreat into account.

Despite the limitations of the modeling approach used in this study, its results are in a good agreement with previous research, suggesting that the PDD method is capable of capturing runoff regimes adequately. However, there are numerous ways to improve precision of the obtained results in the future.

Certain simplifications of the temperature-index approach applied in this study were discussed in Sections 5.1.5 and 5.3, such as the choice of degree-day factors, the use of static standard deviation for daily temperature, the one-step threshold for distinguishing between solid and liquid precipitation and the lack of retention and glacier retreat components. Despite these limitations, the PDD model performed competently and provided a feasible approach for modeling runoff. In this section, possible further improvements are outlined and analyzed.

Simulations of runoff during 1981-2019 suggest that the ratio of solid and liquid precipitation will experience a shift, and rain will become a more common precipitation form due to increasing annual temperatures. Less snow on the glacier surface will lead to an earlier exposure of the glacier surface to solar radiation and will also lead to lower surface albedo, resulting in accelerated glacier melt and retreat. Consequently, the shrinking glacier area and volume may lead to alterations in the glacier contribution to total runoff, which can be important during the ablation period. Therefore, introducing a more appropriate rain/ snow partitioning scheme, a glacier retreat component, or incorporating supraglacial hydrology processess, debris accumulation and consequent effects on albedo and retreat rates and other complex physical mechanisms into the PDD model may considerably increase the precision of model-based estimates for glacier contributions in the future.

Another significant factor influencing model performance is the input data provided by climate products. More complex surface energy balance models (SEB) require more complex climate settings, such as, for example, energy fluxes and wind speed. Even though the seNorge climate dataset exhibites the most reliable performance for modeling runoff with the PDD model, more advanced approaches require climate datasets that can provide more complex climate variables. In this study, the PDD method allowed for the evaluation of the temperature and precipitation records derived from the global climate reanalysis, ERA5-Land, which is provided with a coarser spatial resolution (~ 9 km) against seNorge that lacks forcings necessary for surface energy balance models. Such analyses are essential for understanding whether global data sets perform reasonably well on small scales of glacier basins in order to invest into model experiments with more advanced approaches. Furthermore, in certain parts of the world, the lack of high-quality observational data necessitates the involvement of global datasets for studying the diverse impacts of climate change.

6. Conclusion

This study introduces an inter-disciplinary approach by merging methodologies across social and physical sciences to shed light on the possible impacts of climate change-induced glacier retreat on the hydropower industry and the population in Norway. It combines climate models and observations with a positive degree day (temperature index) model to reconstruct historical glacier runoff patterns and potential future streamflow scenarios in four highly glacierized catchments in Norway. The use of different climate datasets significantly influences the runoff model performance; therefore, a range of in-situ measurements has been utilized to evaluate the Norwegian observational dataset seNorge, the state-of-the-art global climate reanalysis, and selected RCM outputs in search of the best performing data product for modeling past runoff regimes in Norway. Based on a basin-scale evaluation of the regional climate model (RCM) performance during the historical period, a bias-corrected version of the RCM from the EURO-CORDEX initiative has been selected to drive future runoff projections (2020-2100) under two future greenhouse gas (GHG) concentration scenarios, RCM 4.5 and 8.5. Temperature and precipitation fields from all climate datasets were downscaled to accommodate local, small-scale geographic conditions used as an input in the PDD model. Finally, semi-structured open-ended interviews with experts from Statkraft, one of the most prominent companies in the Norwegian energy market, have been carried out to evaluate the probable impacts of changes in the runoff regimes on the Norwegian hydropower industry and society.

Findings of the PDD simulations revealed considerable variations in annual total discharges throughout the last 40 years (1981-2019). These runoff changes align well with broader glacier changes observed in the same period, such as fluctuations in the surface mass balance and glacier extents. The results imply an increase in runoff in all four catchments between 1981 and 2000, followed by a sharp decline in discharge during 2000 – 2012 and a subsequent return to high discharge regimes between 2012 and 2019 in the basins of Austdalsbreen and Rembesdalskåka. In contrast, runoff at Bondhusbrea increased slowly but steadily between 2001 and 2019. Engabreen, on the other hand, demonstrated exceedingly high annual discharge values between 2000 and 2005 with a decrease afterward.

Seasonally, runoff demonstrates more distributed patterns over the calendar year. After the turn of the 21st century, a shift occurred in the runoff, resulting in higher monthly discharges earlier in the year, with the most significant increases in May and June at three out of four glaciers. The second half of the analyzed period (2001-2019) also saw an increase in autumn discharge in every catchment, as opposed to a reduced runoff in late summer (August). While the peak flow was often registered in July, with relatively frequent peak flows occurring in June in the first twenty years of the examined period (1981-2000), it started emerging more frequently in August after 2000.

When examining the degree of glacier contribution to total runoff, the last two decades (2001-2019) have brought about an apparent increase of approximately 3-5 % in the combined contribution of glacier and snowmelt at Austdalsbreen and Rembesdalskåka. At Engabreen and Bondhusbrea, direct glacier runoff contribution to annual total discharge has remained stable over the past 40 years, oscillating around ~ 20 % and 8%, respectively. These inferences agree well with earlier studies suggesting that the contribution of glaciers to the total basin level runoff rises with increasing climate continentality.

As opposed to the relatively stable runoff regimes at Engabreen and Bondhusbrea during the historical period, future projections under the RCP 4.5 scenario indicate larger fluctuations in the runoff from these two glaciers than at the other two locations. Nevertheless, at all four sites, runoff is projected to remain stable under the intermediate RCP scenario until the end of the 21st century. In contrast, runoff under the RCP 8.5 scenario is predicted to increase more significantly, particularly after 2080, compared to the RCP 4.5 scenario. According to the model simulations, the most prominent runoff increase is expected at Engabreen, particularly between 2085 and 2095.

In terms of shares of the contributing sources in the future total runoff, the input from snowmelt is expected to diminish, whilst rain is to play a more influential role to varying degrees at different locations. The projections driven by RCP 4.5 mostly differ from those under the RCP 8.5 scenario by the degree of decline in the snowmelt contribution to the total discharge, with the RCP 8.5 scenario suggesting a considerably larger decrease. Based on the RCP 4.5 model output, the direct contribution of glaciers is expected to remain stable during the 21st century. At the same time, the RCP 8.5 projection demonstrates a slightly decreased relative contribution of glacier melt to the total runoff in 2020-2100 relative to 2020. The actual decrease in the future relative contribution of glacier melt is likely even more substantial, given that the glacier extent in this study is treated as static during the whole period (2020-2100), leading to substantial biases in the glacier runoff projections. Moreover, as the ratio of solid precipitation decreases throughout the 21st century, the glacier ice melt will be intensified at every location due to the formation of supraglacial hydrological systems, earlier exposure of glacier surface to solar radiation, and lower surface albedo, increasingly promoting glacier melt and retreat. The inferences of the absolute glacier runoff contributions to the future discharge should therefore be regarded as first-order approximations and must be treated with caution.

Regardless of potential significant reductions in glacier cover and runoff contributions, experts from Statkraft expect a modest impact of such changes on the hydropower industry in Norway for various reasons. Firstly, as runoff projections demonstrate, there is no indication of decreasing total runoff towards the end of the 21st century. The most significant change is expected in the runoff sources with a shift towards rain; thus, liquid precipitation will most likely compensate for the snow and glacier melt loss. The most prominent actors in the Norwegian hydropower industry are continually monitoring climate change-related issues that might affect production and pose a severe threat to facilities and the population. Such issues involve a sudden, unexpected increase in streamflow due to altered seasonality, frequency, or magnitude of runoff that may lead to intense flooding. Since a significant expansion of an already established hydropower system is not expected in Norway, the potential impacts of glaciers will mostly affect currently operating hydropower facilities with existing climate change adaptation strategies. However, Norwegian energy companies are investing in hydropower development in other parts of the world, such as Asia or South America, where the disappearance of glaciers may lead to more substantial freshwater-related issues in the future.

Concluding remarks

In Norway, increases in precipitation are projected to compensate for the decreasing contribution of glacier melt to the total runoff in the foreseeable future. However, dry summer periods have occurred more frequently in the last ten years than previously, and when dry conditions persist over long intervals, the importance of glaciers as a freshwater resource may increase drastically. Such effects will most likely escalate with increasing distance from the coast, where regions with larger climate continentality will be impacted most profoundly. It remains unclear how this will affect Norway's energy production, where 96% of the electricity consumption is generated by hydropower. To date, reports are contradicting, but experts predict a more pronounced development of other renewable energy sources in Norway, mitigating pressure on the hydropower industry. However, the time-frame required for such a large-scale energy transition is unknown, leaving question marks regarding the adaptation of energy production to climate change in Norway.

References

Aeronautics, United States National, and Space Administration. 2019. "New Version of the ASTER GDEM."

Andreassen, L. M., H. Elvehøy, B. Kjøllmoen, and R. V. Engeset. 2016. "Reanalysis of long-term series of glaciological and geodetic mass balance for 10 Norwegian glaciers." *The Cryosphere* 10 (2):535-552. doi: 10.5194/tc-10-535-2016.

Andreassen, Liss M., Hallgeir Elvehøy, Bjarne Kjøllmoen, and Joaquín M. C. Belart. 2020. "Glacier change in Norway since the 1960s – an overview of mass balance, area, length and surface elevation changes." *Journal of Glaciology* 66 (256):313-328. doi: 10.1017/jog.2020.10.

Andreassen, Liss M., Hallgeir Elvehøy, Bjarne Kjøllmoen, Rune V. Engeset, and Nils Haakensen. 2005. "Glacier mass-balance and length variation in Norway." *Annals of Glaciology* 42:317-325. doi: 10.3189/172756405781812826.

Andreassen, Liss Marie, Hallgeir Elvehøy, Tómas Jóhannesson, J. Oerlemans, Stein Beldring, and Michiel Van den Broeke. 2006. *Modelling the climate sensitivity of Storbreen and Engabreen, Norway*.

Andreassen, Liss Marie, Solveig Winsvold, Frank Paul, and Jon Hausberg. 2012. *Inventory of Norwegian Glaciers*.

Armstrong, Richard L., Karl Rittger, Mary J. Brodzik, Adina Racoviteanu, Andrew P. Barrett, Siri-Jodha Singh Khalsa, . . . Betsy Armstrong. 2019. "Runoff from glacier ice and seasonal snow in High Asia: separating melt water sources in river flow." *Regional Environmental Change* 19 (5):1249-1261. doi: 10.1007/s10113-018-1429-0.

Beniston, Martin, Daniel Farinotti, Markus Stoffel, Liss Marie Andreassen, Erika Coppola, Nicolas Eckert, . . . Christian Vincent. 2018. "The European mountain cryosphere: A review of its current state, trends, and future challenges." *The Cryosphere* 12:759-794. doi: 10.5194/tc-12-759-2018.

Bosson, J.-B., M. Huss, and E. Osipova. 2019. "Disappearing World Heritage Glaciers as a Keystone of Nature Conservation in a Changing Climate." *Earth's Future* 7 (4):469-479. doi: https://doi.org/10.1029/2018EF001139.

Calov, Reinhard, and Ralf Greve. 2005. "A semi-analytical solution for the positive degree-day model with stochastic temperature variations." *Journal of Glaciology* 51 (172):173-175. doi: 10.3189/172756505781829601.

Chen, Jiyang, and Atsumu Ohmura. 1990. "On the influence of Alpine glacieis on runoff." *IAHS Publication (Hydrology in Mountainous Regions. I-Hydrological Measurements; the Water Cycle)* 193.

Dunn, Kevin. 2016. "Interviewing." In *Qualitative Research Methods in Human Geography*, edited by Iain Hay, 149-189. Canada: Oxford University Press.

Dyrrdal, Anita Verpe, Frode Stordal, and Cristian Lussana. 2018. "Evaluation of summer precipitation from EURO-CORDEX fine-scale RCM simulations over Norway." *International Journal of Climatology* 38 (4):1661-1677. doi: https://doi.org/10.1002/joc.5287.

Elvehøy, H., R. Engeset, L. M. Andreassen, J. Kohler, Y. Gjessing, and H. Björnson. 2002. "Assessment of possible jökulhlaups from Lake Demmevatnet in Norway." *IAHS Publ.* 271.

Engelhardt, M., T. V. Schuler, and L. M. Andreassen. 2014. "Contribution of snow and glacier melt to discharge for highly glacierised catchments in Norway." *Hydrol. Earth Syst. Sci.* 18 (2):511-523. doi: 10.5194/hess-18-511-2014.

Engelhardt, Markus, Thomas V. Schuler, and Liss M. Andreassen. 2015. "Sensitivities of glacier mass balance and runoff to climate perturbations in Norway." *Annals of Glaciology* 56 (70):79-88. doi: 10.3189/2015AoG70A004.

Engelhardt, Markus, Thomas Vikhamar Schuler, and Liss Marie Andreassen. 2012. "Evaluation of gridded precipitation for norway using glacier mass-balance measurements." *Geografiska Annaler: Series A, Physical Geography* 94 (4):501-509. doi: 10.1111/j.1468-0459.2012.00473.x.

Engeset, R. 2016. Hvordan lages vær- og snødata for seNorge.no og XGEO.no?

Environment, German Advisory Council on. 2011. "Pathways towards a 100% Renewable Electricity System. Special Report."

Eurelectric. 2011. "Hydropower in Europe. Powering Renewables."

Farinotti, D., V. Round, M. Huss, L. Compagno, and H. Zekollari. 2019. "Large hydropower and water-storage potential in future glacier-free basins." *Nature* 575 (7782):341-344. doi: 10.1038/s41586-019-1740-z.

Farrell , Susan. 2016. "Open-Ended vs. Closed-Ended Questions in User Research."

Fowler, H. J., S. Blenkinsop, and C. Tebaldi. 2007. "Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling." *International Journal of Climatology* 27 (12):1547-1578. doi: https://doi.org/10.1002/joc.1556.

Gardner, Alex S., Martin J. Sharp, Roy M. Koerner, Claude Labine, Sarah Boon, Shawn J. Marshall, . . . David Lewis. 2009. "Near-Surface Temperature Lapse Rates over Arctic Glaciers and Their Implications for Temperature Downscaling." *Journal of Climate* 22 (16):4281-4298. doi: 10.1175/2009JCLI2845.1.

Gebremedhin, Alemayehu, and Jarle De Oliveira Granheim. 2012. "Is there a space for additional renewable energy in the Norwegian power system? Potential for reduced global emission?" *Renewable and Sustainable Energy Reviews* 16 (3):1611-1615. doi: https://doi.org/10.1016/j.rser.2011.11.032.

Glen, Stephanie. 2020. "RMSE: Root Mean Square Error." https://www.statisticshowto.com/probability-and-statistics/regression-analysis/rmse-root-mean-square-error/.

Gobiet, Andreas, Sven Kotlarski, Martin Beniston, Georg Heinrich, Jan Rajczak, and Markus Stoffel. 2014. "21st century climate change in the European Alps—A review." *Science of The Total Environment* 493:1138-1151. doi: https://doi.org/10.1016/j.scitotenv.2013.07.050.

Graabak, Ingeborg, Stefan Jaehnert, Magnus Korpås, and Birger Mo. 2017. "Norway as a Battery for the Future European Power System—Impacts on the Hydropower System." *Energies* 10:2054. doi: 10.3390/en10122054.

Güttler, Ivan, Igor Stepanov, edo Brankovi, Grigory Nikulin, and Colin Jones. 2015. "Impact of Horizontal Resolution on Precipitation in Complex Orography Simulated by the Regional Climate Model RCA3." *Monthly Weather Review* 143 (9):3610-3627. doi: 10.1175/MWR-D-14-00302.1.

Hallé, Danielle A.M. 2020. "Predicting Runoff for a Drinking Water Catchment in Southern Greenland." *NTNU.*

Hanssen-Bauer, Inger, Eirik Førland, Ingjerd Haddeland, Hege Hisdal, Deborah Lawrence, Stephanie Mayer, . . . Bjørn Ådlandsvik. 2017. *Climate in Norway 2100 – a knowledge base for climate adaptation*. Oslo: Norwegian Centre for Climate Service's.

Hazeleger, W., X. Wang, C. Severijns, S. Ştefănescu, R. Bintanja, A. Sterl, . . . K. van der Wiel. 2012. "EC-Earth V2.2: description and validation of a new seamless earth system prediction model." *Climate Dynamics* 39 (11):2611-2629. doi: 10.1007/s00382-011-1228-5.

He, Z. H., J. Parajka, F. Q. Tian, and G. Blöschl. 2014. "Estimating degree-day factors from MODIS for snowmelt runoff modeling." *Hydrol. Earth Syst. Sci.* 18 (12):4773-4789. doi: 10.5194/hess-18-4773-2014.

Heikkilä, U., A. Sandvik, and A. Sorteberg. 2011. "Dynamical downscaling of ERA-40 in complex terrain using the WRF regional climate model." *Climate Dynamics* 37 (7):1551-1564. doi: 10.1007/s00382-010-0928-6.

Hock, Regine, Peter Jansson, and Ludwig N. Braun. 2005. "Modelling the Response of Mountain Glacier Discharge to Climate Warming." In *Global Change and Mountain Regions: An Overview of Current Knowledge*, edited by Uli M. Huber, Harald K. M. Bugmann and Mel A. Reasoner, 243-252. Dordrecht: Springer Netherlands.

Huss, M., G. Jouvet, D. Farinotti, and A. Bauder. 2010. "Future high-mountain hydrology: a new parameterization of glacier retreat." *Hydrol. Earth Syst. Sci.* 14 (5):815-829. doi: 10.5194/hess-14-815-2010.

Jackson, Miriam, and Galina Ragulina. 2014. Inventory of glacier-related hazardous events in Norway. Norwegian Energy and Water Directorate.

Jacob, Daniela, Claas Teichmann, Stefan Sobolowski, Eleni Katragkou, Ivonne Anders, Michal Belda, . . . Volker Wulfmeyer. 2020. "Regional climate downscaling over Europe:

perspectives from the EURO-CORDEX community." *Regional Environmental Change* 20 (2):51. doi: 10.1007/s10113-020-01606-9.

Janssens, Ives, and Philippe Huybrechts. 2000. "The treatment of meltwater retention in mass-balance parameterizations of the Greenland ice sheet." *Annals of Glaciology* 31:133-140. doi: 10.3189/172756400781819941.

Jóhannesson, Tómas, Andreas Ahlstrøm, Liss Marie Andreassen, Helgi Björnsson, Mattias Woul, Hallgeir Elvehøy, . . . Valentina Radić. 2006. "The impact of climate change on glaciers and glacial runoff in the Nordic countries."

Jóhannesson, Tómas, Oddur Sigurdsson, Tron Laumann, and Michael Kennett. 1995. "Degree-day glacier mass-balance modelling with applications to glaciers in Iceland, Norway and Greenland." *Journal of Glaciology* 41:345-358. doi: 10.3189/s0022143000016221.

Jones, Colin, Ulrika Willén, Anders Ullerstig, and Ulf Hansson. 2004. "The Rossby Centre Regional Atmospheric Climate Model Part I: Model Climatology and Performance for the Present Climate over Europe." *Ambio* 33:199-210. doi: 10.1579/0044-7447-33.4.199.

Kartverket. 2019. "DTM 10 Terrengmodell (UTM33)."

Kendon, Elizabeth J., Nigel M. Roberts, Catherine A. Senior, and Malcolm J. Roberts. 2012. "Realism of Rainfall in a Very High-Resolution Regional Climate Model." *Journal of Climate* 25 (17):5791-5806. doi: 10.1175/JCLI-D-11-00562.1.

Kienzle, Stefan W. 2008. "A new temperature based method to separate rain and snow." *Hydrological Processes* 22 (26):5067-5085. doi: https://doi.org/10.1002/hyp.7131.

Kjellström, Erik, Lars Bärring, Stefan Gollvik, Ulf Hansson, Colin Jones, Patrick Samuelsson, . . . Klaus Wyser. 2005. *A 140-year simulation of European climate with the new version of the Rossby Centre Regional Atmospheric Climate Model (RCA3)*. Vol. 108.

Kjellström, Erik, Grigory Nikulin, Ulf Hansson, Gustav Strandberg, and Anders Ullerstig. 2011. "21st century changes in the European climate: uncertainties derived from an ensemble of regional climate model simulations." *Tellus A* 63 (1):24-40. doi: https://doi.org/10.1111/j.1600-0870.2010.00475.x.

Kjøllmoen, Bjarne, L. M. Andreassen, Hallgeir Elvehøy, and Miriam Jackson. 2019. Glaciological investigations in Norway 2018. Norwegian Water and Energy Directorate.

Landgren, O. A., J. E. Haugen, and E. J. Førland. 2014. "Evaluation of regional climate model temperature and precipitation outputs over Scandinavia." *Climate Research* 60 (3):249-264.

Lappegard, Gaute, Stein Beldring, Lars A. Roald, Torill Engen-Skaugen, and Eirik J. Førland. 2006. Projection of future streamflow in glaciated and non-glaciated catchments in Norway. Norwegian Water and Energy Directorate (NVE).

Laumann, Tron, and Niels Reeh. 1993. "Sensitivity to climate change of the mass balance of glaciers in southern Norway." *Journal of Glaciology* 39 (133):656-665. doi: 10.3189/S0022143000016555.

Machguth, H., P. Rastner, Tobias Bolch, Nico Mölg, Louise Sørensen, Gudfinna Adalgeirsdottir, . . . Xavier Fettweis. 2013. "The future sea-level rise contribution of Greenland's glaciers and ice caps." *Environmental Research Letters* 8:025005. doi: 10.1088/1748-9326/8/2/025005.

Marzeion, B., and A. Nesje. 2012. "Spatial patterns of North Atlantic Oscillation influence on mass balance variability of European glaciers." *The Cryosphere* 6 (3):661-673. doi: 10.5194/tc-6-661-2012.

Masson, Valéry, Jean-Louis Champeaux, Fabrice Chauvin, Christelle Meriguet, and Roselyne Lacaze. 2003. "A Global Database of Land Surface Parameters at 1-km Resolution in Meteorological and Climate Models." *Journal of Climate* 16 (9):1261-1282. doi: 10.1175/1520-0442-16.9.1261.

McGuirk, Pauline M., and Phillip O'Neill. 2016. "Using Questionairres in Qualitative Human Geography." In *Qualitative Research Methods in Human Geography*, edited by Iain Hay, 246-274. Canada: Oxford University Press.

Michelangeli, P.-A., M. Vrac, and H. Loukos. 2009. "Probabilistic downscaling approaches: Application to wind cumulative distribution functions." *Geophysical Research Letters* 36 (11). doi: https://doi.org/10.1029/2009GL038401.

Muñoz-Sabater, J. 2017. "ERA5-Land: A new state-of-the-art Global Land Surface Reanalysis Dataset."

Muñoz Sabater, J. 2019. "ERA5-Land monthly averaged data from 1981 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). 10.24381/cds.68d2bb30."

Nash, J. E., and J. V. Sutcliffe. 1970. "River flow forecasting through conceptual models part I — A discussion of principles." *Journal of Hydrology* 10 (3):282-290. doi: https://doi.org/10.1016/0022-1694(70)90255-6.

Nesje, Atle, Øyvind Lie, and Svein Olaf Dahl. 2000. "Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records?" *Journal of Quaternary Science* 15 (6):587-601. doi: https://doi.org/10.1002/1099-1417(200009)15:6<587::AID-JQS533>3.0.CO;2-2.

Räisänen, J., U. Hansson, A. Ullerstig, R. Doescher, P. Graham, C. Jones, . . . U. Willén. 2003. "GCM driven simulations of recent and future climate with the Rossby Centre coupled atmosphere - Baltic Sea regional climate model RCAO."

Räisänen, J., U. Hansson, A. Ullerstig, R. Döscher, L. P. Graham, C. Jones, . . . U. Willén. 2004. "European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios." *Climate Dynamics* 22 (1):13-31. doi: 10.1007/s00382-003-0365-x.

Raju, K. S., and D. N Kumar. 2018. "Downscaling techniques in climate modeling." In *Impact of Climate Change on Water Resources* 77-105. Singapore: Springer.

Rasmussen, LA. 2007. "Spatial extent of influence on glacier mass balance of North Atlantic circulation indices." *Terra Glacialis* 11:43–58.

Rogerson, P.A. 2006. *Statistical Methods for Geography: A Student's guide. Second Edition*. London: Saga Publications.

Rogozhina, I., and D. Rau. 2014. "Vital role of daily temperature variability in surface mass balance parameterizations of the Greenland Ice Sheet." *The Cryosphere* 8 (2):575-585. doi: 10.5194/tc-8-575-2014.

Rummukainen, M., J. Raeisaenen, A. Ullerstig, B. Bringfelt, U. Hansson, P. Graham, and U. Willen. 1998. "RCA-Rossby Centre regional atmospheric climate model: model description and results from the first multi-year simulation."

Rummukainen, M., J. Räisänen, B. Bringfelt, A. Ullerstig, A. Omstedt, U. Willén, . . . C. Jones. 2001. "A regional climate model for northern Europe: model description and results from the downscaling of two GCM control simulations." *Climate Dynamics* 17 (5):339-359. doi: 10.1007/s003820000109.

Saloranta, T.M. 2020. "A static simple threshold to separate solid and liquid precipitation in the seNorge precipitation data set."

Samuelsson, Patrick, Colin G. Jones, Ulrika Willén, Anders Ullerstig, Stefan Gollvik, Ulf Hansson, . . . Klaus Wyser. 2011. "The Rossby Centre Regional Climate model RCA3: model description and performance." *Tellus A* 63 (1):4-23. doi: https://doi.org/10.1111/j.1600-0870.2010.00478.x.

Seguinot, Julien. 2013. "Spatial and seasonal effects of temperature variability in a positive degree-day glacier surface mass-balance model." *Journal of Glaciology* 59 (218):1202-1204. doi: 10.3189/2013JoG13J081.

Shiklomanov, Igor. 1993. "World fresh water resources." In *Water in Crisis: A Guide to the World's Fresh Water Resources* edited by Peter H. Gleick. New York: Oxford University Press.

SMHI. 2015. "Rossby Centre regional atmospheric model, RCA4." accessed 2020.10.12. https://www.smhi.se/en/research/research-departments/climate-research-rossby-centre2-552/rossby-centre-regional-atmospheric-model-rca4-1.16562.

Statkraft. 2010. "Brochure for Sima hydropower plant." accessed 2019.12.21.

Strandberg, Gustav, Lars Bärring, Ulf Hansson, Christer Jansson, Colin Jones, Erik Kjellström, . . . Shiyu Wang. 2014. *CORDEX scenarios for Europe from the Rossby Centre regional climate model RCA4.*

Trachsel, M., and A. Nesje. 2015. "Modelling annual mass balances of eight Scandinavian glaciers using statistical models." *The Cryosphere* 9 (4):1401-1414. doi: 10.5194/tc-9-1401-2015.

Trzaska, Sylwia, and Emilie Schnar. 2014. "A review of downscaling methods for climate change projections." In *African and latin american resilience to climate change (ARCC)*. USAID.

Undén, Per, Laura Rontu, Heikki Järvinen, Peter Lynch, Javier Calvo-Sanchez, Gerard Cats, . . . J. García-Moya. 2002. "HIRLAM-5 scientific documentation."

United Nations Environment Programme, UNEP. 2002. "Vital Water Graphics – An overview of the state of the World's fresh and marine waters."

Vandeskog, Silius Mortensønn, Marion Haugen, and Thordis Linda Thorarinsdottir. 2020. Evaluation of bias corrected precipitation output from the EURO-CORDEX climate ensemble. In *Report at the Norwegian Computing Center*.

Vaughan, D.G., J.C. Comiso, I. Allison, J. Carrasco, G. Kaser, R. Kwok, . . . T. Zhang. 2013. "Observations: Cryosphere." In *Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley, 317-382. United Kingdom and New York: Cambridge University Press, Cambridge.

Wake, L. M., and S. J. Marshall. 2015. "Assessment of current methods of positive degree-day calculation using in situ observations from glaciated regions." *Journal of Glaciology* 61 (226):329-344. doi: 10.3189/2015JoG14J116.

Wilby, Robert, Jessica Troni, Yvan Biot, L. Tedd, Bruce Hewitson, Doug Smith, and R. Sutton. 2009. "A Review of Climate Risk Information for Adaptation and Development Planning." *International Journal of Climatology* 29:1193-1215. doi: 10.1002/joc.1839.

Winkler, Stefan, Hallgeir Elvehøy, and Atle Nesje. 2009. "Glacier fluctuations of Jostedalsbreen, western Norway, during the past 20 years: the sensitive response of maritime mountain glaciers." *The Holocene* 19 (3):395-414. doi: 10.1177/0959683608101390.

Winsvold, S. H., L. M. Andreassen, and C. Kienholz. 2014. "Glacier area and length changes in Norway from repeat inventories." *The Cryosphere* 8 (5):1885-1903. doi: 10.5194/tc-8-1885-2014.

Wolff, M. A., K. Isaksen, A. Petersen-Øverleir, K. Ødemark, T. Reitan, and R. Brækkan. 2015. "Derivation of a new continuous adjustment function for correcting wind-induced loss of solid precipitation: results of a Norwegian field study." *Hydrol. Earth Syst. Sci.* 19 (2):951-967. doi: 10.5194/hess-19-951-2015.

Xu, Mingxing, Ming Yan, Jiancheng Kang, and Jiawen Ren. 2012. "Comparative studies of glacier mass balance and their climatic implications in Svalbard, Northern Scandinavia, and Southern Norway." *Environmental Earth Sciences* 67 (5):1407-1414. doi: 10.1007/s12665-012-1585-3.

Yang, Wei, Johan Andréasson, L. Graham, Jonas Olsson, Jörgen Rosberg, and Fredrik Wetterhall. 2010. "Distribution based scaling to improve usability of RCM regional climate model projections for hydrological climate change impacts studies." *Hydrology Research* 41. doi: 10.2166/nh.2010.004.

Appendices

Appendix I: Information letter for participants in the interviews

Information letter to management informants

In this letter, you will receive information about the purpose of Levente Samu's master's project and what participation will entail for you.

Purpose

This study intends to evaluate the historical contribution of glacier changes to run-off volume and timing, create future glacier melt projections, and assess the socio-economic importance of melt-water for hydropower development and local communities by joining the forces of physical and human geography. Methods will be based on numerical analysis of historical climate, glacier, and catchment run-off data. Determining climatic vs. glacier factors in run-off trends will be supported by gridded precipitation and near-surface air temperature data for the selected study sites. Regional variations will be weighed by selecting study sites in four different regions with locations varying from north to south and with oceanic, precipitation rich to continental regions. A Positive Degree Day model will be applied to estimate past and predict future glacier melt-water volumes. Concerning socio-economic aspects of the study, it is intended to reveal information and the perceptions of hydrology/ hydropower experts by carrying out semi-structured open-ended interviews.

Who is responsible for the research project?

The Department of Geography, NTNU is responsible for the project.

What does it mean to participate?

Participation in the project involves participating in an interview in written form. Answering the questions will take roughly one hour, but it depends on how relevant you will find them and how long do you wish to express your opinions. Through the interviews, I intend to shed light on issues that could not be observed by solely analyzing available datasets and modelling. The questions will focus on the possible effects glaciers and climate-change triggered glacier fluctuations pose to the Norwegian hydropower industry and to the population in general. Answers will be stored electronically on an NTNU affiliated computer where no third party can access it.

Participation is voluntary

All participation in the project is voluntary. While the project is in progress, you can withdraw from participating or withdraw certain information provided through the interview at any time and without reason. If you withdraw, all information about you will be deleted. It will have no negative consequences for you if you do not want to participate or later choose to resign.

Your privacy – how we store and use your information

The information about you will only be used for the purposes described in this information paper. The data will be treated confidentially and in accordance with the data protection regulations. The personal data collected includes your name, e-mail address, occupation, and the informant's role within the hydropower industry or else. Only my supervisor and I will have access to this information, and your information will be stored separately from other data. In the finished master's thesis, you will be anonymized, and no information will be published that directly or indirectly tells you who you are.

What happens to your information when we finish the research project?

All personal data and written answers will be deleted at the end of the master's thesis project, which is expected to be at December 15, 2020.

Your rights

As long as you can be identified in the data material, you are entitled to:

- gain access to what personal data is registered about you,
- rectify personal data about you,
- delete personal information about you,
- obtain a copy of your personal data (data portability), and
- to lodge a complaint with the Data Protection Officer or the Norwegian Data Protection Authority about the processing of your personal data.

What gives us the right to process personal data about you?

We process information about you based on your consent. The Norwegian Centre for Research Data (NSD) has considered the processing of personal data in this project to be in accordance with the data protection regulations.

Where can I find out more?

If you have any questions about the study or would like to exercise your rights, please contact:

- Master student Levente Samu, by *e-mail: leventes@stud.ntnu.no;* or *phone: 40183516*
- Irina Rogozhina, by *email: irina.rogozhina@ntnu.no*, Department of Geography, NTNU
- NSD – Norwegian Centre for Research Data, by *e-mail: personverntjenester@nsd.no;* or *phone: 55582117*

Yours sincerely,

Levente Samu	Irina Rogozhina
Master student	*Professor at Dep. of Geography* (*Supervisor*)

I have received and understood information about the project *Impacts of Climate-Change Induced Glacial Retreat on Hydrology and its Socio-Economic Consequences in Norway*, and have had the opportunity to ask questions. I agree to:

- to participate in a written interview about the topic
- that information about me is published so that I can be recognized - optional

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(Signed by respondent, date)

Appendix II: Every slope lapse rate generated from various climate datasets

	Temperature slope lapse rates (based on ERA5-Land)		
	SLR_temp	SLR_summer	SLR_winter
Austdalsbreen	-0,0064	-0,0070	-0,0060
Bondhusbrea	-0,0055	-0,0056	-0,0049
Engabreen	-0,0067	-0,0052	-0,0080
Rembesdalskaka	-0,0039	-0,0048	-0,0036

	Precipitation slope lapse rates (based on ERA5-Land)		
	SLR_precip	SLR_precip_summer	SLR_precip_winter
Austdalsbreen	-0,00950	0,01530	-0,00208
Bondhusbrea	-0,00240	-0,00160	-0,02360
Engabreen	0,02350	0,01740	0,04140
Rembesdalskaka	-0,02460	-0,02740	-0,03850

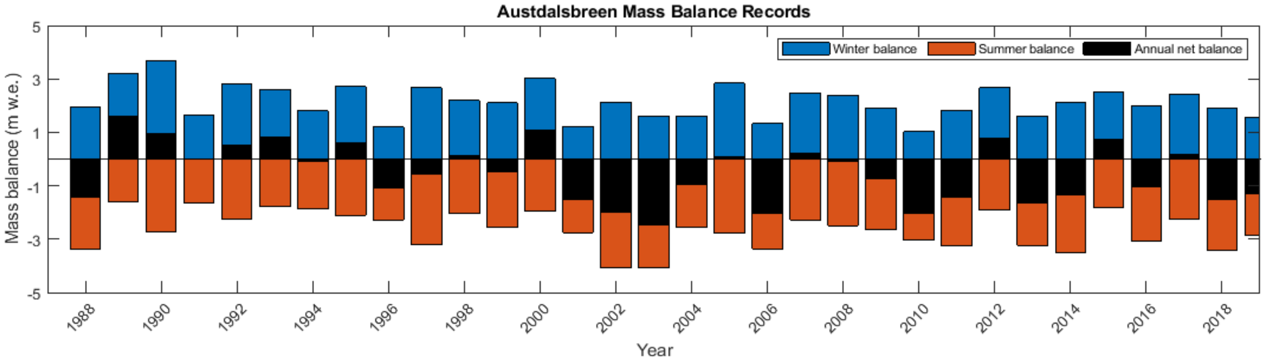
	Temperature slope lapse rates (from weather stations)		
	SLR_temp	SLR_summer	SLR_winter
Engabreen	-0,006200	-0,006100	-0,006200

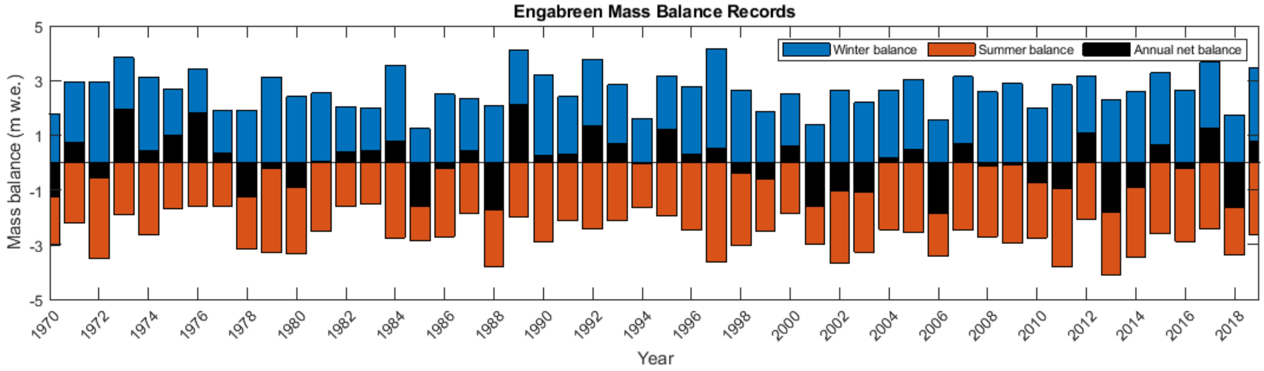
	Slope lapse rates temperature (based on literature)		
	SLR (°C km $^{-1}$)	Source	Comment
Canadian Arctic	- 4,9	Gardner et.al., 2009	Based on four High-Arctic Canadian glaciers
Norway	- 5,8	Jóhannesson et.al.,1995	Summer
Iceland	- 5,3	Jóhannesson et.al.,1995	Summer

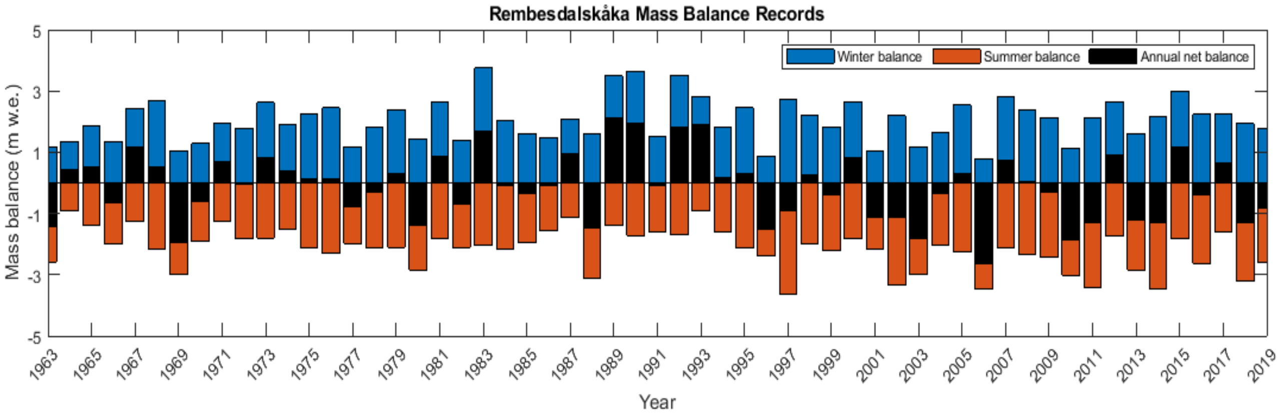
	Temperature slope lapse rates (based on SeNorge)		
	SLR	SLR summer	SLR winter
Austdalsbreen	-0,0058	-0,0061	-0,0051
Bondhusbrea	-0,0063	-0,0065	-0,0060
Engabreen	-0,0068	-0,0067	-0,0067
Rembesdalskaka	-0,0062	-0,0062	-0,0058

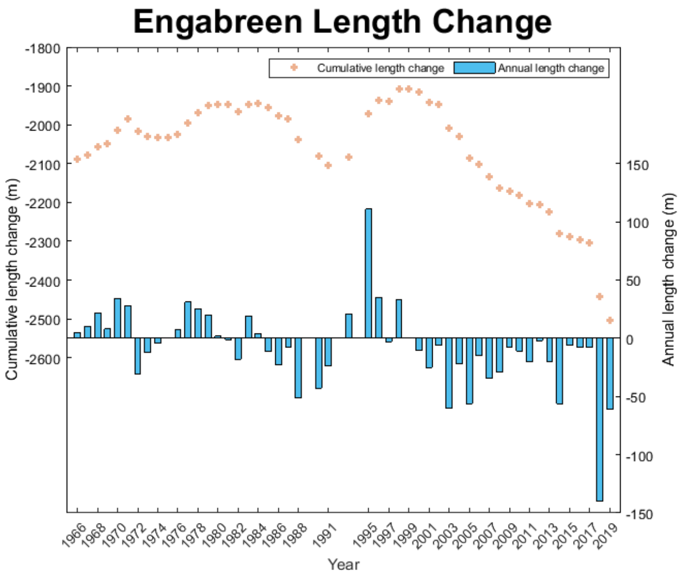
	Precipitation slope lapse rates (based on SeNorge)		
	SLR_precip	SLR_precip_summer	SLR_precip_winter
Austdalsbreen	0,0287	0,0174	0,0521
Bondhusbrea	0,0785	0,0770	0,1185
Engabreen	0,0702	0,0525	0,1451
Rembesdalskaka	0,0353	0,0353	0,0355

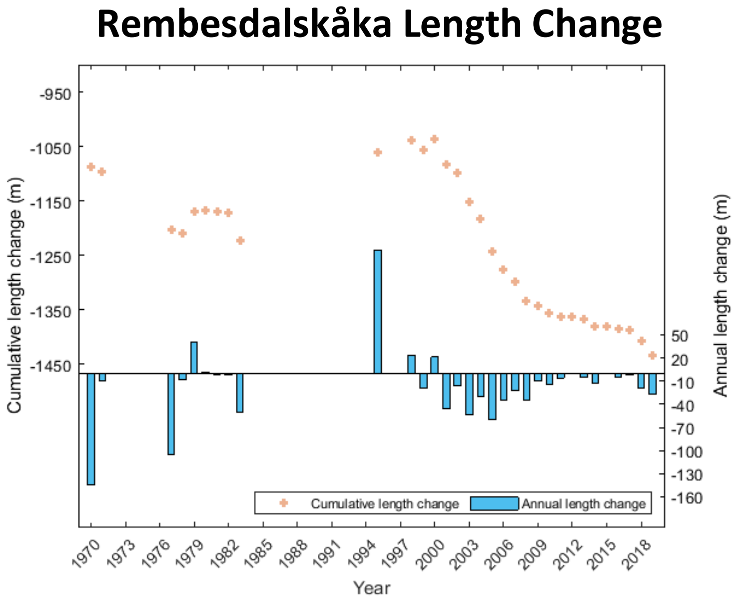
Appendix III: The remainder of glacier changes, including mass balance records and length measurements, and frontal positions/ extent. Source of data: NVE.



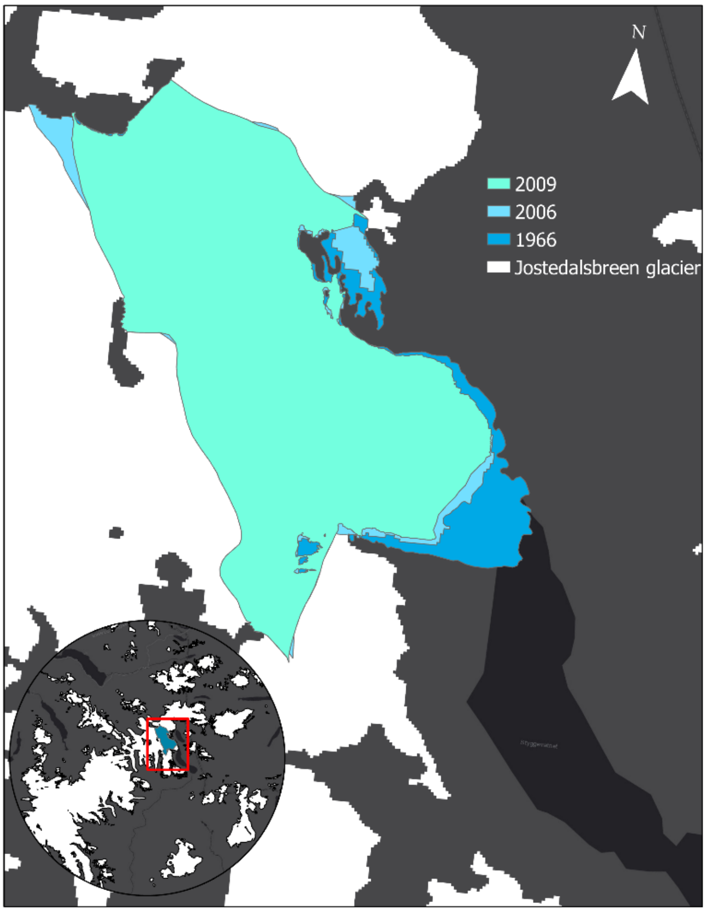




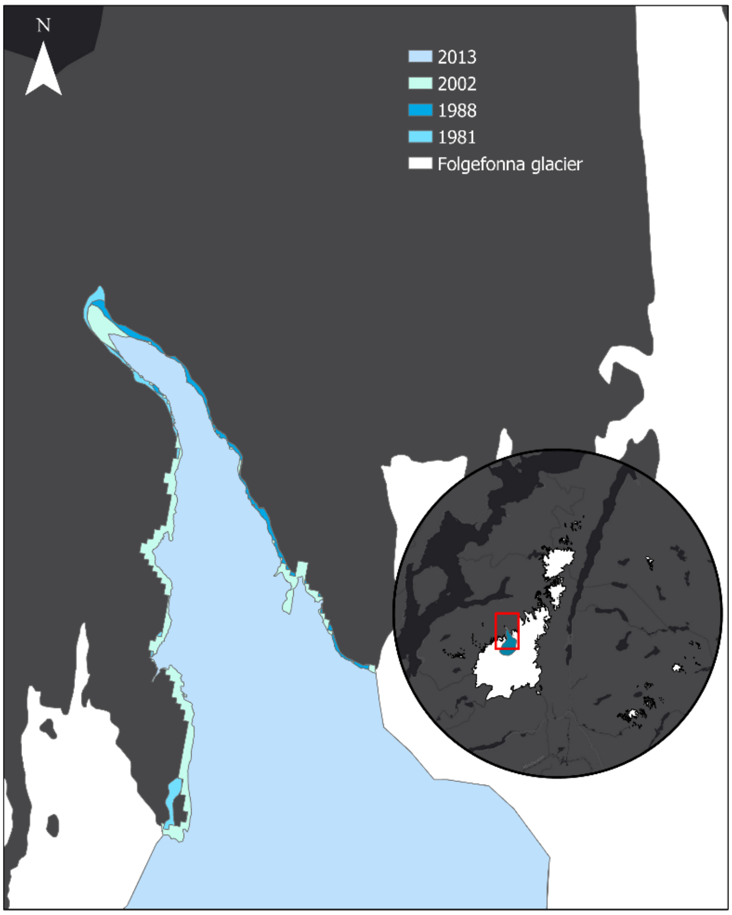




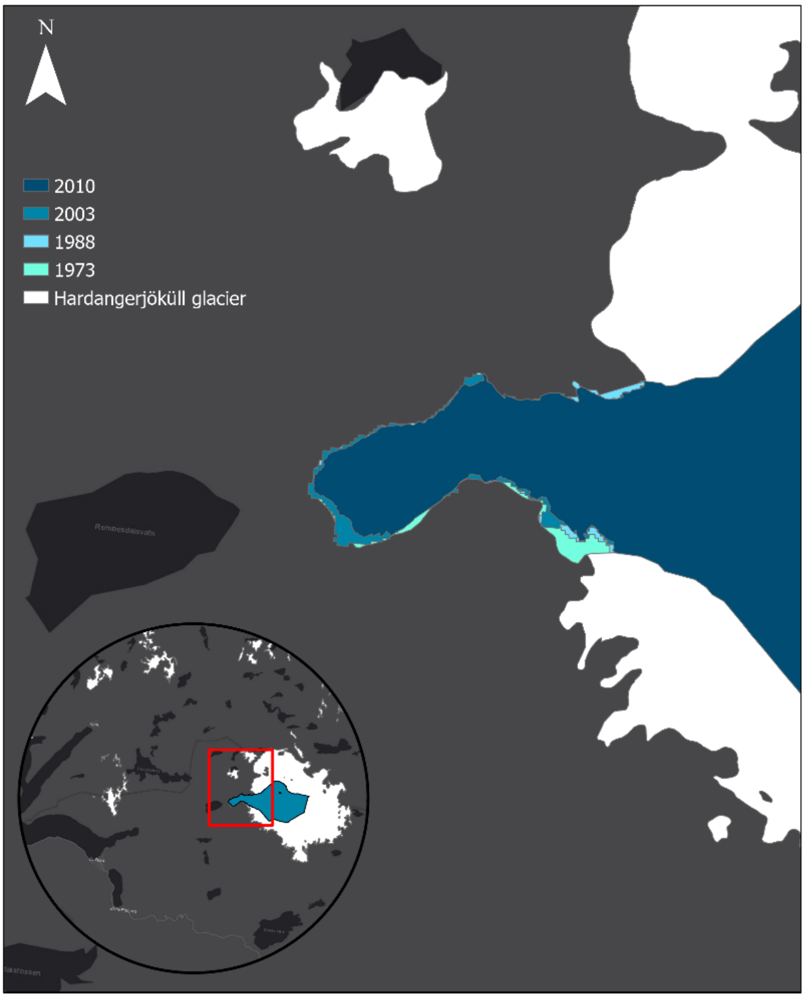
Austdalsbreen Area



Bondhusbrea Area



Rembesdalskåka Area



Levente Samu

Impacts of climate change on glacier runoff and hydropower production in Norway

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