Glacier mass-balance and discharge modeling

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December 2013

Dissertation

for the degree of

Philosophiae Doctor (PhD)

Department of Geosciences
Faculty of Mathematics and Natural Sciences
University of Oslo
Norway

Series of dissertations submitted to the
Faculty of Mathematics and Natural Sciences, University of Oslo
No. 1458

ISSN 1501-7710

Cover: Inger Sandved Anfinsen.
Printed in Norway: AIT Oslo AS.

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Science cannot solve the ultimate mystery of nature.
And that is because, in the last analysis, we ourselves are part of nature and therefore part of the mystery that we are trying to solve.

– Max Planck

Nigardsbreen, Vestlandet (Western Norway)

Summary

Glaciers are among the most frequently used natural phenomena to illustrate ongoing global warming. Retreating glacier tongues and the reduction of glacierized areas are visible all over the world. Changes in glacier volume affect both the river runoff regime downstream and sea level. In Norway, mountain glaciers and associated streamflow are of particular importance since the electricity sector relies on hydropower. The spatial and temporal distribution of glacier mass-balance and discharge measurements from glacierized catchments is therefore biased towards demands from hydropower utilization.

This study investigates glacier mass balance and associated meltwater discharge together with their spatial and temporal variations. A mass-balance model has been adapted to the glacierized area in Norway using temperature and precipitation data from *seNorge* (http://www.senorge.no) and potential solar radiation as input. The data from *seNorge* are available for the whole country on a 1 km horizontal grid and on a daily time step from 1957 to present. The gridded data from *seNorge* are evaluated using winter mass balances at point locations on glaciers in different regions across the country. Results indicate that the *seNorge* data are suitable for mass-balance modeling, but further adjustment of the precipitation data should be performed.

The modeled mass balances for the glacierized area of Norway yield a overview of spatial averaged glacier mass balance from 1961-2010. Seasonal mass balances show large year-to-year variability. Nevertheless, the winter and annual glacier mass balance show positive trends over 1961-2000 followed by a remarkable decrease in both summer and winter balances in the years 2000-2010 resulting in an average annual mass balance of close to -1 m w.e. (water equivalent) a^{-1} for the first decade of the 21st century. The mass balance sensitivities to temperature and precipitation variations are much larger for glaciers in maritime than for continental climate conditions. Despite the large extent of the Norwegian mainland from north to south, the mass balance sensitivities to temperature and precipitation changes show a stronger gradient from west to east.

For the period 1961-2012, discharge is modeled for three catchments with a glacierization between 50-70 % situated along a west-east profile in southern Norway. The model simulations reveal an increase of the relative contribution from glacier melt to discharge from less than 10 % in the early 1990s to 15-30 % in the late 2000s. The decline in precipitation by 10-20 % in the same period was therefore overcompensated by increased glacier melt resulting in an increase of the annual discharge by 5-20 %. Discharge from the westernmost glacier catchment is most sensitive to changes in precipitation. In contrast, discharge from the easternmost catchment is most sensitive to changes in summer temperatures where glacier melt has become a large contributor to discharge during summer. Especially for more continental glaciers in Norway, this may lead to reduced summer discharge when their glacier area continues to decrease. For the three studied catchments, the increasing continentality from west to east yields larger differences in glacier mass balance, specific discharge and sensitivities to changes in temperature or precipitation than differences in catchment size or glacier coverage. However, plateau glaciers may have the largest potential to discharge changes in the future, when ongoing temperature rise continues.

Furthermore, an assessment of meltwater contribution to discharge is performed for a catchment area in northern India. For this purpose, the glacier mass-balance model is implemented in a large-scale hydrological model that simulates discharge. The catchment area has a size of 5406 km^2 of which 14 % is permanently covered with snow or ice. During the period 1997-2001, the contribution of glacier- and snowmelt in this catchment was accounting on average for 41 % of the annual discharge.

The model results are an analysis of variations in the past, but can also serve to discuss changes in the present and prospective evolutions of glaciers and their impact on discharge from glacierized catchments in connection to further climate changes.

Sammendrag

Isbreer er et av de naturlige fenomenene som oftest brukes for å illustrere den pågående globale oppvarmingen. Breutløp som trekker seg tilbake og isbreer som krymper observeres over hele verden. Volumendringer av isbreer påvirker både avrenningsregimet i elver nedstrøms, samt havnivået. I Norge er isbreer og tilhørende avrenning spesielt viktig, fordi energisektoren er basert på vannkraft. Fordelingen av massebalanse- og avrenningsmålinger gjenspeiler derfor ofte både i rom of tid kravene til vannkraftens utnyttelse.

I denne studien blir massebalansen på breer i Norge og tilhørende avrenninger undersøkt, og i tillegg romlige og tidsmessige variasjoner. En modell for å beregne massebalanser er justert til å passe til hele landets breområdet. Modellen bruker temperatur- og nedbørsdata fra *seNorge* (http://www.senorge.no) og potensiell solstråling som inndata. *SeNorge*-dataene er tilgjengelige for hele Norge i en horisontal oppløsning på 1 km og som døgnverdier fra 1957 til i dag. *SeNorge*-dataene evalueres ved å sammenligne modellert vintermassebalanser og punktmålinger fra isbreer i ulike regioner av landet. Resultatene viser at *seNorge*-data er egnet for massebalansemodellering, men ytterligere tilpassing av nedbørsdata anbefales.

De modellerte massebalansene gir en oversikt over breers massebalanse for hele det norske breområdet i perioden 1961-2010. Massebalansene viser store årlige svingninger. Likevel viste både vinter- og nettobalansene en positiv utvikling i tidsrommet 1961-2000 fulgt av en påfølgende betydelig nedgang i både sommer- og vinterbalanser i årene 2000-2010. Dette førte til en markant negativ nettobalanse og en gjennomsnittlig minking i bretykkelse på omtrent 1 m årlig i denne perioden. Massebalansen til breer som befinner seg i et maritimt klima er mer følsomme for temperatur- og nedbørsendringer, enn de som ligger lengre inne i landet. Selv om det norske fastlandet er langstrakt fra nord til sør, er forskjellene i massebalansesensitivitet størst fra vest til øst.

I tillegg ble vannføringen samt til bidraget av smeltevann modellert for tre avløpsfelt langs et vest-øst profil over langfjellet: Ålfotbreen, Nigardsbreen og Storbreen. Avløpsfeltene har en isbreandel på mellom 50-70 %. Modellsimuleringene viser en økning av relativt bidrag til bresmelting, fra en prosentandel på mindre enn 10 % i begynnelsen av 1990-tallet, til 15-30 % i slutten av 2000-tallet. Nedgangen i nedbør på 10-20 % i samme periode ble mer enn oppveid av den økte bresmelting, som førte til i en økning av årlig avrenning på 5-20 %. Avrenningen fra Ålfotbreen, det vestligste avløpsfeltet, er mest følsom for endringer i nedbør. Avrenning fra Storbreen, det østligste avløpsfeltet, er på sin side mest følsom til endringer i sommertemperatur. I dette område har bresmeltingen blitt en betydelig del av sommerens avrenning. Etter hvert som breområdene fortsetter å krympe, kan imidlertid breene østafjells oppleve en redusert avrenning i sommermånedene. Klimaforskjellene fra øst til vest fører til at de tre overnevnte avløpsfeltene har større ulikheter i massebalanse, da spesielt i forbindelse med avrenning og sensitiviteten for temperatur- og/eller nedbørsendringer, enn ulikheter knyttet til størrelsen på avløpsfelt eller relativ breprosenten. Dersom temperaturene fortsetter å stige, kan imidlertid platåbreer ha det største potensialet for avrenningsendringer i fremtiden.

Til sist vurderes bidraget av smeltevann til vannføringen i et avløpsfelt i Nord-India. Massebalansemodellen blir knyttet til en hydrologisk modell som simulerer vannføring. Avløpsfeltet har en størrelse på 5406 km^2 hvorav 14 % er permanent dekket med snø eller is. I årene 1997-2001 bidro bre- og snøsmelting i dette avløpsfeltet til gjennomsnittlig vannføring på 41 % årlig.

Modellresultatene kan brukes til å analysere variasjoner i fortid, pågående forandringer i nåtiden og kan også være nyttig for å estimere fremtidige utviklinger av breer og deres innvirkning på vannføring i forbindelse med ytterligere klimaendringer.

Zusammenfassung

Gletscher gehören zu den am häufigsten verwendeten Naturerscheinungen um die fortschreitende globale Erwärmung zu veranschaulichen. Zurückziehende Gletscherzungen oder schrumpfende Gletscherflächen sind weltweit zu beobachten. Volumenänderungen von Gletschern betreffen sowohl das Abflussregime flussabwärts als auch den Meeresspiegel. In Norwegen sind die Gletscher und die damit verbundenen Schmelzwasserabflüsse von besonderer Bedeutung, da der Energiesektor auf Wasserkraft beruht. Die Verteilung von Gletschermassenbilanz- und Wasserabflussmessungen spiegelt daher sowohl in Raum als auch Zeit Vorgaben der Wasserkraftnutzung wider.

In dieser Studie werden die Gletschermassenbilanzen und damit verbundene Schmelzwasserabflüsse in Norwegen, sowie ihre räumlichen und zeitlichen Schwankungen untersucht. Ein Computermodell zur Berechnung dieser Massenbilanzen wurde auf die vergletscherte Fläche in Norwegen angepasst. Das Modell verwendet Temperatur- und Niederschlagsdaten von *seNorge* (http://www.senorge.no), sowie potenzielle Sonnenstrahlung als Eingangsdaten. *SeNorge* stellt für ganz Norwegen Tageswerte von 1957 bis zur Gegenwart in einer horizontalen Auflösung von 1 km zur Verfügung. Diese Rasterdaten von *seNorge* werden mit Hilfe von Wintermassenbilanzen an Punktmessungen bewertet, die von Gletschern in verschiedenen Regionen Norwegens stammen. Die Ergebnisse zeigen, dass die *seNorge*-Daten für Massenbilanzmodellierung geeignet sind, jedoch eine weitere Anpassung der Niederschlagsdaten durchgeführt werden sollte.

Die modellierten Massenbilanzen der vergletscherten Fläche Norwegens von 1961-2010 liefern einen Überblick der landesweit gemittelten Gletschermassenbilanzen. Die Massenbilanzen weisen große jährliche Schwankungen auf. Dennoch zeigen die Winter- und Nettobilanzen positive Entwicklungen von 1961-2000. Der nachfolgende deutliche Rückgang sowohl der Sommer- als auch Winterbilanzen in den Jahren 2000-2010 ergeben eine deutlich negative Nettobilanz und eine mittlere Höhenabnahme der Gletscher von rund 1 m jährlich in der ersten Dekade der 21. Jahrhunderts. Die Empfindlichkeit der Massenbilanzen auf Temperatur- und Niederschlagsveränderungen sind für Gletscher in ozeanisch geprägten Klimazonen viel stärker ausgeprägt als für jene weiter im Landesinneren. Trotz der großen Nord-Süd-Ausdehnung des norwegischen Festlandes sind die Unterschiede in den Massenbilanzempfindlichkeiten größer von West nach Ost.

Für den Zeitraum 1961-2012 werden die Gesamtabflüsse sowie Schmelzwasserbeiträge von drei Einzugsgebiete mit einem Gletscheranteil zwischen 50-70 % modelliert, die entlang eines West-Ost-Profils in Südnorwegen liegen. Dazu werden die Empfindlichkeiten der Abflüsse gegenüber Temperatur- und Niederschlagsänderungen aufgezeigt. Die Modellsimulationen zeigen eine Zunahme des relativen Beitrages von Gletscherschmelze von weniger als 10 % in den frühen 1990er Jahren auf 15-30 % in den späten 2000er Jahren. Der Rückgang der Niederschläge um 10-20 % im gleichen Zeitraum wurde dadurch mit Gletscherschmelze überkompensiert, was zu einer Erhöhung des jährlichen Wasserabflusses von 5-20 % führte. Die Abflussmenge vom westlichsten Einzugsgebiet reagiert am empfindlichsten auf Veränderungen des Niederschlages. Im Gegensatz dazu reagiert die Abflussmenge vom östlichsten Einzugsgebiet am empfindlichsten auf Veränderungen der Temperaturen im Sommer, wo Gletscherschmelze in-zwischen einen wesentlichen Beitrag zum

Abfluss darstellt. Besonders für weniger ozeanisch beeinflusste Gletscher in Norwegen kann dies kann zu verminderten Sommerabflüssen führen, wenn ihre Gletscherflächen weiter abnehmen. Für die drei untersuchten Einzugsgebiete sind die Unterschiede in sowohl Gletschermassenbilanzen, Schmelzwasserabflüssen als auch deren Empfindlichkeiten gegenüber Temperatur- oder Niederschlagsänderungen eher auf die zunehmende Kontinentalität des Klimas von West nach Ost als auf Unterschiede in Einzugsgebietsgröße oder Vergletscherungsgrad zurückzuführen. Allerdings hat ein Gletscher auf einer Hochfläche ein größeres Potenzial auf Abflussmengenänderungen, wenn sich der gegenwärtige Temperaturanstieg weiter fortsetzt.

Schließlich erfolgt eine Abschätzung des Schmelzwasserbeitrages für ein Einzugsgebiet in Nordindien. Hier wird das Gletschermassenbilanzmodell in einem großräumigen hydrologischen Modell eingebaut, das Abflüsse simuliert. Das Einzugsgebiet hat eine Größe von 5406 km^2, wovon 14 % ständig mit Schnee oder Eis bedeckt sind. Während der Jahre 1997-2001 stellte Gletscher- und Schneeschmelze in diesem Einzugsgebiet durchschnittlich 41 % des mittleren Jahresabflusses dar.

Die Modellergebnisse zeigen eine Analyse von Variationen in der Vergangenheit und von gegenwärtigen Veränderungen, dienen aber auch für Abschätzungen von zukünftige Gletscherentwicklungen und deren Einfluss auf Abflüsse aus vergletscherten Einzugsgebieten in Verbindung mit weiteren Klimaänderungen.

Acknowledgments

In the beginning of a new stage in life, moving to a new country and starting research on a new topic, one has to find a way through the challenges presented. Fortunately, I found myself very quickly at home in Norway.

I wish to address my first personal acknowledgment to my principle supervisors Thomas Vikhamar Schuler from the Department of Geosciences and Liss Marie Andreassen from the glacier group of the Norwegian Water Resources and Energy Directorate (NVE). They both inspired me with new ideas and their excellent guidance is the basis of this dissertation.
Thomas also inspired and motivated me to complete my first marathon. Although the following statement is meant for a marathon, there are still some parallels with finishing a dissertation: *It tests the boundaries of both physical and mental endurance, the ability to keep moving forward in the face of extreme pain, fatigue, physical damage and sometimes emotional despair.*
Finally, both challenges have been successfully completed.

I also want to express special gratitude to Bjarne Kjøllmoen from NVE and Even Loe from Statkraft. I am very thankful to have joined them several times on fieldwork that involved helicopter flights and driving snowmobiles on glaciers. I am grateful that I could that you helped me to collect data for this study.

Thanks also to the "warm-lunch group" and all its various members throughout the years. Only with the decent lunches did I have enough power for the sometimes long afternoons.

Thanks to the student organizations of both OSI Dans and OSI Fjell that helped me to forget about science and offered grateful and necessary changes to the daily routines with dancing lessons, cabin weekends and hiking trips.

Glaciers occur in areas in the world that are among the least influenced by human activities and glaciologists around the world share the interest in spectacular areas. Having never been outside of Europe before, courses and conferences brought me to places many people can only dream of: Alaska, Canada, San Francisco, China and eventually Tibet. The latter was appropriately advertised as a "once in a lifetime experience". Besides science, the social, cultural and natural discoveries during all these journeys are invaluable.

Finally I want to express special thanks to those who raised me and allowed me to be whatever I wanted to be. Thank you very much indeed!

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Chapter 1

Introduction

1.1 Motivation

Climate change will be one of the major challenges to mankind in the 21st century. Changes are not restricted to temperature rise, but also impact the water cycle through alterations in precipitation, evaporation and surface runoff, affecting drinking water availability, agriculture and hydropower utilization. The observed global mean sea level has risen 0.20 m over the period 1901-2010 and a further increase of 0.26-0.98 m is very likely to occur by 2100 (IPCC, 2013).

Glaciers are among the most obvious evidences of the ongoing climate change. Despite differences in local conditions and response times, glaciers in the whole world show a largely homogeneous trend of retreat (WGMS, 2008, 2013). Glaciers affect human activities in mountainous regions as well as further downstream since glacier meltwater is an important source for drinking water and irrigating systems. Glacier retreat and changes in the associated streamflow regime is therefore expected to have great socio-economic effect on populated areas in the world which are dependent on glacier meltwater as water storage (Jones, 1999), especially the Himalayas (e.g. Immerzeel and others, 2013; Bolch and others, 2012; Sharma and others, 2000) and the Andes (e.g. Chevallier and others, 2011; Vuille and others, 2008; Bradley and others, 2006). Recent studies estimate the contribution to global sea-level rise from all glaciers and ice sheets to 1.48 $\pm$ 0.26 mm a^{-1} for the period 2003-2010 (Jacob and others, 2012) to 1.80 $\pm$ 0.47 mm a^{-1} for the period 2005-2011 (Chen and others, 2013). However, the glacier contribution from all small glaciers to sea level rise is difficult to estimate (e.g. Giesen and Oerlemans, 2013; Braithwaite and Raper, 2002) since they show a large regional heterogeneity (Radić and others, 2014; Radić and Hock, 2011).

Already in the 18th and 19th century, glaciers were subject to written or pictorial descriptions (e.g. Walcher, 1773; Finsterwalder and Schunk, 1887). Such descriptions were mainly due to local incidences (e.g. Foss, 1750), or inspired by painters (e.g. Forbes, 1853) or travelers (e.g. von Buch, 1810). Systematic glacier length observations from glaciers around the world are hardly available for the time before the mid 19th century (Leclercq and Oerlemans, 2012) but glaciers gained scientific attraction in connection with their response to climate variations. Nye (1960) found that glacier front variations are a result of complex combinations of short and long term climatic perturbations. Applying inverse modeling techniques, glacier length variations were used by Lüthi and others (2010) to reconstruct glacier volumes and by Oerlemans (2005) to reconstruct temperature signals for different regions of the world. Glaciers are considered to be very sensitive to climate variations (Kaser and others, 2006) by changes in glacier thickness, area coverage and mass balance. However, systematic glacier mass-balance measurements are only performed on a limited number of glaciers due to the often remote location of glaciers in inaccessible and high-mountain terrain where ground-based measurements are expensive and time consuming. In addition, the observed glacier mass-balance measurements are biased towards easily accessible glaciers in Europe and North America (Braithwaite, 2002). To compensate for the lack of measurements there exist different methods of reconstructing seasonal glacier mass balances (e.g. Hoelzle and others, 2003; Huss and others, 2008a, 2010a; Marzeion and others, 2012). Glaciers and their changes through time are also increasingly observed by satellites with a wide range of different sensors (Paul and others, 2013). Whereas satellite measurements such as laser altimetry can provide an overview of the glacier mass change in larger regions (e.g. Kääb and others, 2012), those measurements are an integrated average over an area and over several years, omitting small-scale spatial and temporal variations.

The ongoing climate change also exerts a large impact on glacierized catchments. In the Alps, increased runoff between 1974 and 2004 from highly glacierized catchments are linked to increased air temperatures rather than increased precipitation (Pellicciotti and others, 2010). As glaciers are a considerable water reservoirs acting on different time scales (Jansson and others, 2003), long-term changes of glacierization impacts water resources and is of high importance for hydroelectricity production (Finger and others, 2012). In Norway, 98 % of the electricity is generated by hydropower (Gebremedhin and De Oliveira Granheim, 2012) and all catchments regulated for hydropower include 60 % of the total glacier area (Andreassen and others, 2012b). Many glaciers in Norway are threatened to disappear by the end of the 21st century (Giesen and Oerlemans, 2010). The long-term forecast for western Norway indicates that a rise in the summer temperature by about 2 °C by the end of the 21st century. This will first result in a doubling of the glacier melt period for some glaciers (Andreassen and Oerlemans, 2009) and eventually in a reduction of the total glacier area by about 34 % by 2100 (Nesje and others, 2008).

Glacier discharge has a significant diurnal and annual cyclicity. The glacier melt contributes to the discharge especially during summer. The relative magnitude of the summer peak depends on the percentage of glacier cover in otherwise similar catchments (Huss and others, 2008b). Future discharge from glacierized catchments will undergo significant changes to the current situation. Although future climatic and hydrological projections are subject to large uncertainties climate change will have major impacts on mountain hydrology and the water resource management of mountainous regions. Glacier retreat and the release of freshwater from long-term glacial storage is expected to be a key element in projections of high alpine runoff over the next decades (Huss and others, 2010b). Retreating glaciers can have opposing impacts on runoff. Whereas decreasing glacier volume reduces the reservoir of frozen water, negative mass balance rates lead to an initial increase of melt water runoff. Later, the loss of volume is accompanied by a shrinking of the area and the total runoff from the glacier decreases. Another consequence of retreating glacier volumes is the change in the runoff regime towards earlier runoff peaks with discharge increase during spring but decline during summer (Finger and others, 2012). The seasonal shift of the hydrological cycle and the reduced ice melt generation may force hydropower companies to adapt new water management strategies. As the discharge of glacierized catchments is linked to the glacier mass balance, both glaciological and hydrological applications require a good understanding of mass balance variations. Glacier measurements are therefore important for surveying glacier changes and for understanding the relationship between climate, glaciers and discharge.

In recent years, modeling efforts have contributed to increased understanding of glacier dynamics and hydrological processes. In hydrological models, variation of the glacier extent is often included in a very simplified way. Moreover, these models are often calibrated exclusively using discharge measurements. As discharge consists of the sum of liquid precipitation, snow and glacier melt, errors from different runoff sources could compensate each other. Mass-balance modeling is a prerequisite for the prediction of meltwater discharge and streamflow from glacierized catchments (e.g. Finger and others, 2011; Schaefli and Huss, 2011). One difficulty to reasonably model these effects is the impact of glacier volume changes to variations in areal extent. Although these effects can be described by a glacier flow model, such methods are computationally expensive and their application is restricted to individual glaciers rather than to systems of glaciers on a regional scale. Different approaches to account for area changes have been proposed based on simplified parameterizations (e.g. Bahr and others, 1997; Harrison and others, 2003; Radić and others, 2007; Huss and Farinotti, 2012).

There is a range of surface mass balance models available, spanning from physically-based energy balance models to conceptual temperature index models of different complexity. The applicability of physically-based models is often limited by the lack of available meteorological observations in mountainous regions. Especially the assessment of temperature and precipitation distribution is a crucial component, as they represent the controlling input. Precipitation is the most important input variable for both modeling glacier mass balance (Machguth and others, 2008) or catchment hydrology (Li and others, 2013). For a correct simulation of discharge from glacierized catchments there is still a demand for a better quality control of the glacier models, leading to an improved representation of glaciers in hydrological models.

1.2 Objectives

This study aims to model glacier mass balance and associated meltwater discharge together with spatial and temporal variations.

For this purpose, the main objectives are

- Adapting a mass-balance model to the glacierized area in Norway using gridded temperature and precipitation data and potential solar radiation as input.

- Evaluating the gridded precipitation dataset from *seNorge* using winter mass balances at point locations on glaciers in different regions of Norway.

- Modeling the seasonal glacier mass balances for the glacierized area in Norway using the temperature and precipitation dataset from *seNorge* in order to obtain a complete overview of spatial averaged seasonal glacier mass balances for the period 1961-2010 for all of mainland Norway.

- Modeling annual discharge, glacier melt contribution to discharge and the evolution of the discharge components from three glacierized catchments along a west-est profile in southern Norway for the period 1961-2012.

- Evaluating sensitivities of both seasonal glacier mass balances and annual discharge sums to annual and monthly temperature and precipitation changes.

- Implementing the mass-balance model in a large-scale hydrological model to analyze the meltwater contribution to discharge for a catchment area in northern India.

Chapter 2

Scientific background

2.1 Glaciers and climate

Mountains glaciers develop where mass gain by snowfall (accumulation) over a long time span exceeds mass loss by melting (ablation). According to present terminology of the *Glossary of glacier mass balance and related terms* (Cogley and others, 2011), the sum of annual accumulation c_a and annual ablation a_a over a year is called the annual mass balance. The annual quantity is determined between two consecutive summer minima where the surface reaches its annual minimum, following the stratigraphic method (Østrem and Brugman, 1991).

As continuous accumulation or ablation measurements are hardly available, seasonal quantities of winter mass balance b_w and summer mass balance b_s are used to account for seasonal mass changes at point locations. Together with density information, gained through measurements or assumptions, the quantities are usually converted to water equivalents (w.e.). Neglecting internal processes influencing glacier mass balance such as freezing of rain or meltwater, ablation due to strain heating or melting at the base, the annual glacier mass balance is equal the surface annual mass balance and can be expressed as:

$$b_a \quad = \quad c_a + a_a \quad = \quad b_w + b_s \tag{2.1}$$

The integration over the glacier area yields the annual glacier mass change. The normalization of this mass change to the glacier area A yields the mean glacier-wide specific mass-balance components $B_{w/s/a}$ (in m w.e. a^{-1}):

$$B_{w/s/a} \quad = \quad \frac{1}{A} \int_A b_{w/s/a} \, dA \tag{2.2}$$

The specific surface mass-balance components B_w, B_s and B_a are referred thereinafter as winter, summer and annual glacier mass balance, respectively.

The vast majority of glaciers can be divided into an accumulation zone, where the annual mass balance is positive, and an ablation zone, where the annual mass balance is negative. The two zones are separated by the equilibrium-line altitude (ELA). Despite what its name suggests, this line is not necessarily situated at the same altitude. Due to surface topography, glacier hypsometry, aspect of the glacier or shading effects of surrounding slopes, the microclimate of a glacier can have great influence on the location and the course of the ELA. Especially the regional distribution of snow and its local redistribution by wind on glaciers (e.g. Winstral and Marks, 2002; Dadic and others, 2010) lead to spatial heterogeneity of the local glacier mass balance. For a glacier in equilibrium, the mass gain in the accumulation area above the ELA equals the mass loss in the lower part of the glacier where glacier ice melts during summer after the winter snow has melted away. The remaining snow in the accumulation area transforms within several years through compaction to glacier ice. The annual ELA is highly correlated to the annual glacier mass balance (e.g. Lie and others, 2003) and can therefore be used to monitor climatic conditions (e.g. Porter, 1975).

For a glacier in equilibrium, mass surplus in the accumulation zone and mass deficit in the ablation zone is compensated by transport of mass through ice movements. Any glacier on a slope experiences a force along the slope due to gravity. This leads to a shearing flow through internal deformation (e.g. Singh and Singh, 2001). For a glacier with a temperate base, for which the temperature at the base is at the melting point, an additional basal velocity through sliding on the underlying bedrock adds to the total flow. The velocity of the total flow is dependent on many factors such as ice thickness, the slope, the bedrock topography, the steepness of the mass balance gradient and the annual air temperature. For a detailed review on glacier dynamics, see the book of van der Veen (2013).

In contrast to a common misunderstanding, glacier melt is not a necessary sign of a retreating glacier or a glacier that loses mass. Despite of an obvious melt at the glacier front and a retreat of the glacier tongue, the total ice mass of the glacier can be constant or even increasing. If by glacier flow, less mass is transported downstream towards the glacier front than necessary to compensate for the mass loss in the ablation area, the glacier tongue is very likely to retreat. However, the annual mass balance of the whole glacier could still be zero or even positive. Vice versa, the advance of a glacier tongue and a mass loss of the glacier are no contradiction when the flow rate of a glacier is larger than necessary to compensate for mass loss in the ablation area. The response of a glacier to climate variations is dependent on its geometry, flow dynamics and the specific climatic settings (Oerlemans, 2005). The response time is an integrated reaction of year-to-year variability and long term climate changes (Burke and Roe, 2013; Farinotti, 2013). Oerlemans (2000) explored the effect of stochastic forcing on different glaciers and calculated for the glacier Nigardsbreen in western Norway a standard deviation (σ) of 610 m in glacier length for the period 8500 BC to 2000 AD. Since such a glacier would therefore spend about 5 % of its time outside of $\pm$ 2 σ, fluctuations in the range of 1 km could be expected quite frequently. Since glacier response times to climate changes can range from tens to hundreds of years (Jóhannesson and others, 1989), many glaciers are not in equilibrium with the present climate. Thus, both retreating glaciers and glaciers with a negative mean annual mass balance are not necessarily a sign of climate variations. The retreat can also be induced by an average climate condition for which the glacier is not in equilibrium. A glacier with a low elevation range shows a larger response time in equal climatic conditions. Due to different response times, retreating and advancing glaciers can even occur in regions with similar climate condition.

An extreme example of glacier flow represents a so-called *surge* during which a glacier redistributes mass within a short time (from months to several years). This event is not necessarily related to climatic conditions (e.g. Dunse and others, 2011). During a surge, velocities of up to 4 m h^{-1} can occur (Raymond, 1987). Causes of surges vary (Clarke, 1991). However, they have in common that after several decades up to several centuries of too low glacier flow velocities the mass redistribution of the glacier does not compensate for the mass balance gradient which results in a too steep gradient of the glacier surface. In the years following a surge, the glacier is not in balance to the climate conditions, since it is exposed to reduced annual balances due to a large mass and surface growth of the ablation area. Strictly speaking, a surge-type glacier is not even in equilibrium in the quiescent phase between two surge events, since the mean annual glacier balance is larger than the prevailing climatic conditions would suggest. For a detailed review on glacier surges, see Raymond (1987).

Although glacier length changes are easier to measure than glacier mass changes, changes in the terminus of a glacier are less related to climatic changes than mass changes expressed in the annual glacier mass balance. Dyurgerov and Meier (1999) found that variations of annual mass balances are dominated by variations of winter balances for glaciers in maritime climate conditions, and by variations of summer balances for glaciers in continental climate conditions.

The classical idea of winter accumulation and summer ablation applies to glaciers in Europe and North America where glacier studies evolved. However, many glaciers have different characteristics with both accumulation and ablation mainly occurring in summer. These so called summer accumulation type glaciers are found in a continental summer precipitation climate and dominate in parts of the Andean mountains (Fujita, 2008b), and in the eastern and central Himalayas (Bolch and others, 2012) where most glaciers accumulate mainly during the summer monsoon between June and September (Fujita, 2008a). At these glaciers, processes like internal accumulation and formation of superimposed ice due to retention and refreezing of meltwater is more important than at other glaciers since periods with temperatures around freezing point during summer are more likely to occur (Fujita and others, 2007). These glaciers also dependent on the timing of the monsoon season, since an early start of the wet season delays the summer melt season (Kang and others, 2009). Summer accumulation type glaciers are more vulnerable to global warming, as increasing summer temperatures not only increases the energy available for melt, but also decreases snow accumulation. In addition, reduced summer snowfall reduces the surface albedo and further accelerates melting (Fujita and Ageta, 2000).

To capture the mass changes on glaciers with sparse data coverage or simulate future mass-balance evolutions, mass balance models have been developed to calculate seasonal and annual mass balances and to link glacier mass changes to climate variations.

2.2 Glacier mass balance and discharge models

The importance of gaining knowledge about glacier mass balance and associated meltwater discharge is not restricted to local impacts. The scientific community is trying to improve knowledge of natural processes and to link observed changes to climate variations. Although measurements of both glacier mass balance and discharge from glacierized catchments are available all over the world, these measurements are typically biased toward easily accessible locations and heterogeneous in time and space. In addition, measurements are still sparse in comparison to the large amount of glaciers and glacierized catchments which differ from each other in local characteristics like size, climate settings or sensitivity to climatic changes.

Models can be used to complete available measurements by filling in missing values and to extend measured data series in both time and space. Models that show a reasonable representation of natural processes can also serve to evaluate the sensitivity of these processes to climate variations. To simulate those natural processes, a wide range of models exist spanning a range of different complexity. Most models can be classified being either a physically-based model, where natural processes are described by physical equations, or a empirical model, which are based on an empirical relationship between input variables and the desired output variable. In between, there exist a wide range of conceptual models that might take into account physical laws but still be based on empirical relationships.

Physically-based models describe natural processes to a high degree of accuracy. In addition, such models do not need calibration when all relevant processes are considered. However, they typically consist of many variables and thus require a lot of input data and computational power. Measurements of those input data are usually not available for the whole model domain and extrapolation of measured variables over a model domain introduces additional uncertainty for each variable. Although physically-based models employ the laws of physics to describe natural processes, such model usually cannot describe a physical entity. Thus, also these models rely on assumptions and simplifications of processes. Lack of input data is the main reason for the requirement of simpler models and the development of empirical or conceptual models.

Conceptual models are mostly based on empirical relations, but require a basic understanding of the system. These models may consider physical laws in a simplified form or use parameters with a physical meaning. However, conceptual models cannot easily be transferred to other model domains than for the one they are calibrated. In addition, those models might not be suitable to simulate changes for different climate scenarios. Since the used calibration parameters are based on local domain characteristics and specific climate settings which might not be valid in a changed setting, conceptual models may lead to misleading predictions. The choice of the applied model is therefore strongly dependent of the availability of input data, the local settings and the objective of the study.

Mass-balance models range from simple temperature-index models (e.g. Hock and others, 2009) to distributed energy-balance models (e.g. Le Meur and others, 2007). In between, there exist a wide range of conceptual models like enhanced temperature-index models including shortwave radiation (e.g. Farinotti and others, 2012).

Melt of snow or ice occurs at temperatures > 0 °C. Although melt is correlated to air temperature, it is determined by the energy available for melt Q_{melt}:

$$M = \frac{Q_{\mathrm{melt}}}{\rho_w \cdot L_f} \tag{2.3}$$

where ρ_w is the density of water and L_f the latent heat of fusion. The energy available for melt for an area A at the surface covered by snow or ice can be calculated by integrating the energy balance over this area:

$$Q_{\mathrm{melt}} = \frac{1}{A} \int_A (Q_R + Q_H + Q_L + Q_G + Q_R)\, dA, \tag{2.4}$$

with the net fluxes of radiation (Q_R), sensible heat (Q_H), latent heat (Q_L), ground heat (Q_G), and sensible heat supplied by rain (Q_R). The energy balance describes the physical processes at the surface. However, glacier melt models that are based on the energy balance require input data that are difficult to measure. As an example, turbulent fluxes depend on the wind speed gradients that, if measured at a point location, cannot easily be extrapolated on a glacier surface in a mountainous terrain. To meet this challenge, melt models have been developed which span a wide range of complexities (Hock, 2005). The lack of sufficient input data is the main reason for parametrization of physical processes and the use of empirical approaches.

Empirical melt models take advantage in the strong correlation between melt and air temperature and are therefore called temperature-index models. These models employ in their simplest form only positive air temperature for computing melt of snow and ice by multiplying the sum of positive temperatures (T^+) over a period with an empirical constant. In case of daily mean temperatures, this constant is mostly often called *DDF* (degree day factor):

$$M = DDF * \sum T^+ \tag{2.5}$$

Typically, a daily time step is applied and different *DDFs* for snow and ice are used to account for differences in surface albedo and thus different melt efficiencies of snow and ice. Although these models only use air temperature as input, they produce reliable estimates of summer ablation (e.g. Hock, 2003). To account for the diurnal temperature cyclicity and thus melt on days with positive temperatures during daytime although daily averages are negative, a lower threshold temperature for melt might be used to obtain more realistic melt rates (van den Broeke and others, 2010). On catchment scales, these models often yield a remarkable good performance similar to energy balance models in various parts of the world (see Hock, 2003, for a review). Although short-wave radiation is the dominant component in the energy balance on a glacier surface (e.g. Andreassen and others, 2008; Pellicciotti and others, 2008), fluctuations in annual glacier mass balance are mainly due to changes in temperature and precipitation (Oerlemans, 2005). In addition, air temperature is correlated to sensible heat flux, incoming short-wave and emitted long-wave radiation fluxes. The good performance of those temperature-index models is therefore based on physical reasons (Ohmura, 2001), although air temperature is the only measured variable for computing melt. However, parameters for glacier catchments in different climate settings can vary significantly from each other (Hock, 2003), since e.g. temperature-dependent energy fluxes like the sensible heat fluxes are higher for glaciers in maritime climate conditions (Giesen and others, 2008).

If available, sub-daily temperatures values like hourly data improve model performance significantly by accounting for diurnal variations in melt energy (Tobin and others, 2012). However, the main focus on air temperature does not account for processes that also can have a large impact on snow melt like albedo, wind or air humidity (e.g. Carenzo and others, 2009) and simplifies the complex variety of energy exchange processes to a high degree. To compensate for the deficiencies of using only air temperature for calculating melt, enhanced temperature-index models have been developed that include more variables like potential or measured incoming short-wave radiation, the short-wave radiation balance or the albedo (e.g. Hock, 1999; Pellicciotti and others, 2005). The use of potential short-wave radiation introduces the possibility of diurnal variations in melt rates (e.g. Pellicciotti and others, 2008) and improves model performance since short-wave radiation is the dominant component in the energy balance on a glacier surface.

As for mass-balance models, also hydrological models exist in a wide range of different complexity from simple lumped models to distributed physically-based models. The use of a lumped hydrological model for calculating discharge from a glacier catchment can be justified by a high percentage of glacierization, steep topography and therefore fast discharge, no or sparse vegetation cover and low infiltration to groundwater. In addition, the use of a daily time step in the model simplifies the calculations when discharge is calculated for daily sums. Semidistributed conceptual models can include variable precipitation gradients like the Nordic HBV model (Sælthun, 1996) or account for catchment heterogeneity like the rainfall-runoff model TOPMODEL (TOPography based hydrological MODEL) (Beven and Kirkby, 1979).

For glacierized catchments, the most commonly available data for model calibration are glacier mass-balance and discharge measurements (e.g. Finger and others, 2011). Whereas using only discharge for calibration can yield several parameter sets with similar model performance, the use of glacier mass-balance measurements for parameter calibration increases the performance of conceptual hydrological models in glacierized catchments (e.g. Konz and Seibert, 2010).

2.3 Glaciers in Norway

In the latest version of the *Inventory of Norwegian Glaciers* (Andreassen and others, 2012b), there are defined 2534 glaciers in Norway (Fig. 1 in Article II) spreading over a large latitudinal range (60-70 °N) and covering an area of 2692 ± 81 km^2 (0.8 % of mainland Norway). Although the glaciers are predominantly found in alpine environments south of the Arctic circle, the Norwegian glaciers are often included in Arctic glacier studies (e.g. Dowdeswell and others, 1997; DeWoul and Hock, 2005; Braithwaite, 2005; Oerlemans and others, 2005).

Contemporary mountain glaciers are of particular importance in Norway given their influence on streamflow and thus on regional water supply and hydropower utilization. Studies of glacier length variations indicate that most likely all these glaciers have been melted away at least once during the Holocene and reestablished between 8000 and 4000 BP (e.g. Nesje and others, 2008). Historical documents (such as written documents and paintings) allow reconstruction of the glacier outline and length variations of several outlet glaciers of Jostedalsbreen for the last 300 years (Nussbaumer and others, 2011). Already in the 1860s, the largest glacier of Norway (Jostedalsbreen) was subject to glacier study (Nussbaumer and others, 2011). Among these studies were meteorological observations and photographs of different glaciers. De Seue, a meteorologist from Christiania (now Oslo), revealed that the outlet glacier Briksdalsbreen was advancing after several years of previous retreat (de Seue and Sexe, 1870). Glacier length changes in Norway have been recorded for more than a century (Øyen, 1906). Whereas in Norway, measuring glacier mass balances by satellite data has started with first tests only in the early 1970s (Østrem, 1975), continuous ground-based measurements already started in 1949 on Storbreen (Andreassen and others, 2005). Despite some deviations, mass balances derived from geodetic methods based on aerial photogrammetry, in general agree with the traditionally mass balance measurements (Andreassen and others, 2002).

Between 1980 and 2000 positive mass balances and therefore mass gain of almost all glaciers was observed in Norway (e.g. Hagen, 1996; Andreassen and others, 2005) which was a result of changed atmospheric circulation patterns (Rasmussen and others, 2007a). Increased incidences of strong westerly flow, expressed by increased values of the North Atlantic Oscillation (Hurrell, 1995), led to increased winter precipitation and higher winter mass balances (Dowdeswell and others, 1997). Winter temperatures at the glaciers in Norway are low enough that higher air temperatures during this period did not lead much of the winter precipitation shifting from snow to rain as it did in other parts of the world (e.g. Rasmussen and Conway, 2004; Rasmussen and others, 2007b). In addition, increased westerly flow led to a higher degree of cloud cover and more moist air that resulted in slightly reduced summer ablation (Pohjola and Rogers, 1997). With a short response time of 3-6 years, maritime glaciers of southern Norway advanced by up to 300 m within 10 years (Nesje and Matthews, 2012). After the period of advance in the 1980s and 1990s, present reports indicate a general recession of mountain glaciers also in Norway (e.g. Nesje and others, 2008; Andreassen and others, 2012a). Whereas glacier frontal position changes are generally linked to changes in annual mass balances, the glacier retreat in Norway after the year 2000 seems to occur faster than annual mass balances suggest (Winkler and Nesje, 2009). Many glaciers in Norway are projected to retreat significantly in the 21st century (e.g. Laumann and Nesje, 2009a) or even to disappear by the end of the 21st century (e.g. Johannesson and others, 2006; Giesen and Oerlemans, 2010). As a consequence of decreasing ice volume, the discharge from glacierized catchments is expected to increase by 25-50 % within the next decades (Jóhannesson and others, 2006) before the reduced volume leads to a reduction in discharge.

In Norway, seasonal mass-balance measurements have been performed on 43 glaciers since 1949 (NVE, 2013). In 2013, seasonal mass-balance measurements were performed on 14 glaciers. The measurements are published in reports (e.g. Kjøllmoen and others, 2011) from the Norwegian Water Resource and Energy Directorate (NVE). For five glaciers, located in different regions, continuous glacier mass-balance measurements have been performed for $>$ 40 years (Fig. 2.1). These five regions represent different climate conditions and the selected glaciers in these regions show differences in area and elevation range (Tab. 2.1). For the period 1971-2010, the mean measured seasonal mass balances for these five glaciers vary between +1.5 and +3.8 m w.e. for the winter balances and -1.8 and -3.6 m w.e. for the summer balances. The largest and smallest mass turnover occurs at Ålfotbreen and Storbreen, respectively, the westernmost and easternmost among the selected glaciers in southern Norway. Whereas Storbreen also experienced the largest mass loss among the five selected glaciers, the largest mass gain is observed at Engabreen,

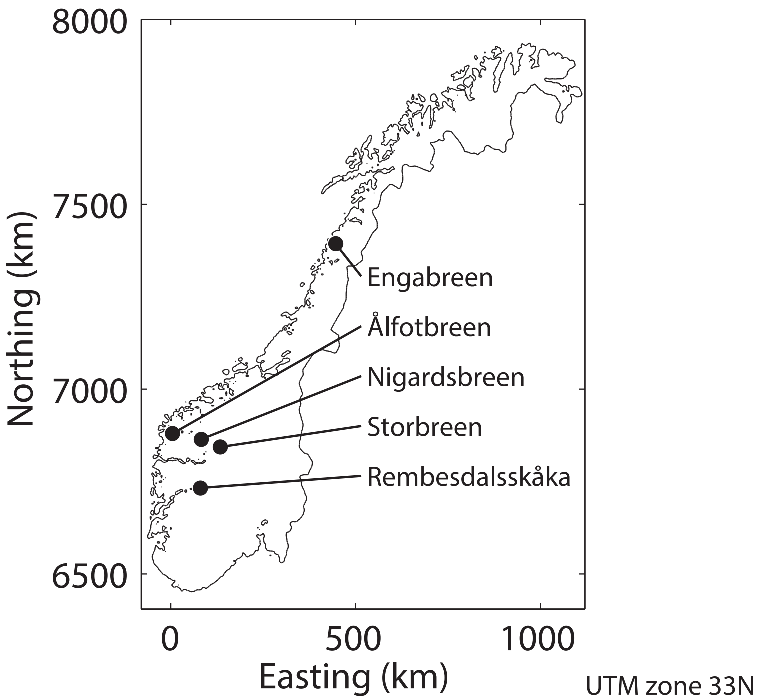

Figure 2.1: Location of five glaciers in Norway with more than 40 years of mass-balance measurements.

Table 2.1: Comparison of the five glaciers shown in Fig. 2.1 in size, associated mapping year, elevation range, measured mean winter (B_w) and summer (B_s) mass balance for the period 1971-2010, and the beginning of continuous mass-balance (m.b.) measurements.

Glacier	Area (km^2)	Mapping year	Elevation (m a.s.l.)	B_w (m w.e.)	B_s (m w.e.)	Start of m.b. measurements
Engabreen	38.7	2008	89-1574	2.92	-2.33	1970
Ålfotbreen	4.5	1997	903-1382	3.80	-3.57	1963
Nigardsbreen	47.2	2009	315-1957	2.39	-2.01	1962
Storbreen	5.1	2009	1400-2102	1.46	-1.76	1949
Rembesdalsskåka	17.1	1995	1020-1865	2.17	-2.03	1963

the northernmost glacier in this study. Except for Storbreen, the decade with the most positive annual mass balances were the 1990s (Fig. 2.2), when the mean mass gain was between +0.5 and +1.0 m w.e. In the 2000s, after three decades of significantly higher mass balances, all five glaciers experienced the lowest mass balance during their respective period of measurements. In addition, for the first time at all five glaciers the 10-year average mass balance was negative. However, the traditional mass-balances measurements are most likely overestimated at Engabreen. Geodetic mass-balance measurements revealed a negative accumulated mass balance at Engabreen already for the period 1968-1985 (Haug and others, 2009). In addition, another glacier in northern Norway shows for the period 1994-2008 a mean annual mass balance of -1.0 m w.e. a^{-1} (Andreassen and others, 2012a).

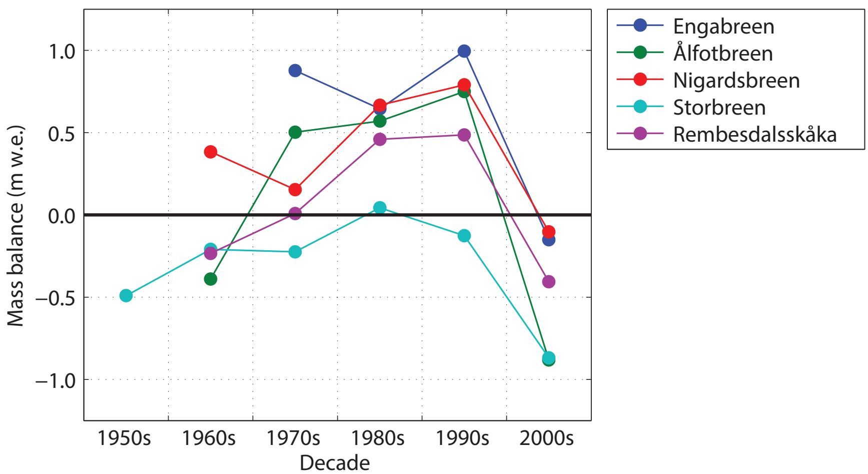

Figure 2.2: 10-year average measured mass balances of the five glaciers shown in Fig. 2.1.

For this study, all available seasonal mass-balance measurements from 42 glaciers for the study period 1961-2010 are used as calibration an validation data to model the mass balance of the total glacierized area of Norway (Article II, section 8.2), and the seasonal mass-balance measurements of Ålfotbreen, Nigardsbreen and Engabreen until 2012 are part of the calibration scheme for discharge modeling for the catchments of these three glaciers (Article III, section 8.3).

Chapter 3

Data and methods

3.1 The *seNorge* dataset

SeNorge (Norwegian for *See Norway*) is a collaboration between the Norwegian Water Resources and Energy Directorate (NVE), the Norwegian Meteorological Institute (met.no) and the Norwegian Mapping Authority (Statens kartverk). It was launched in 2006 and provides on its webpage (http://www.senorge.no) information about snow, water, weather and climate data (Fig. 3.1). In the present version (v. 1.1, 2010), gridded products of daily (06-06 UTC) meteorological and hydrological fields are available at 1 km horizontal resolution for mainland Norway for the period 1957 to present. The gridded data provided by *seNorge* are based on interpolated temperature and precipitation measurements from about 200 stations for temperature and 400 for precipitation. The exact number of data used for the interpolation changes daily depending on automatical and manual data quality control. From the temperature and precipitation data, a degree-day model described by Engeset and others (2004) determines derived quantities such as snow depth, snow water equivalent, fresh snow, snow melt and information like skiing conditions.

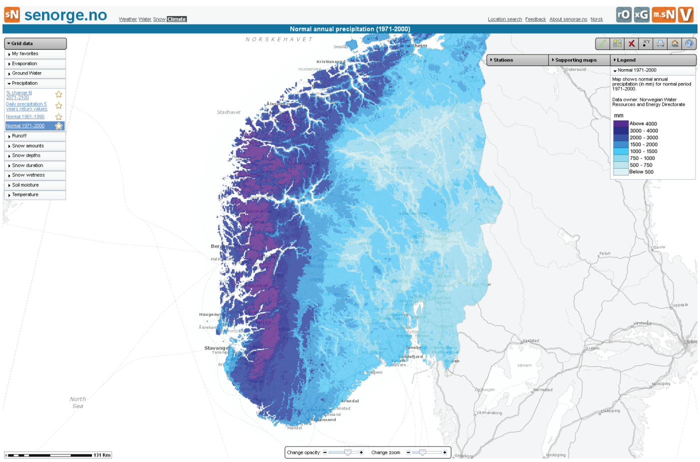

Figure 3.1: Webpage of *seNorge* (http://www.senorge.no); here displaying the mean annual precipitation sum for southern Norway (1971-2000).

Table 3.1: Temperature lapse rates (in °C per 100 m) used in the *seNorge* interpolation scheme.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-0.12	-0.19	-0.46	-0.61	-0.63	-0.63	-0.61	-0.57	-0.55	-0.46	-0.32	-0.16

The interpolation of the measured temperature and precipitation values is done in several steps. For temperature, the measured daily mean values are first projected to sea level (Tveito and others, 2000). For this daily de-trending, regression coefficients based upon monthly mean temperature data are used. These coefficients were calculated from monthly mean temperature data from 1152 stations in Norway, Sweden, Denmark and Finland using stepwise linear regression. Residual kriging (Journel and Huijbregts, 1978) is then used for the spatial interpolation of de-trended temperatures (Tveito and others, 2000). Finally, the interpolated temperatures are readjusted to terrain altitude using a lapse rate that is different for each month (Tab. 3.1).

An evaluation of the *seNorge* temperature data for glacier areas can be performed using measurements that are not used for the seNorge interpolation scheme. Such data are available from two automatic weather stations (AWS) located close to Nigardsbreen at 1630 m a.s.l. (Steinmannen station, operated by Statkraft) and in the ablation zone of Storbreen at 1570 m a.s.l. (Andreassen and others, 2008). In contrast to Nigardsbreen where the AWS is outside the glacier surface, at Storbreen the AWS is located on the glacier and therefore during summer stronger influenced by the glacier surface. The AWS are measuring air temperature since October 2008 and September 2001, respectively. The temperatures from *seNorge*, which were further interpolated to the location of the AWS, are on average 0.6 K higher at Nigardsbreen and 3.6 K higher at Storbreen with largest differences at both sites during winter. Mean monthly temperature lapse rates for *seNorge* which would yield best agreement to the measurements vary between -0.65 and -0.01 °C $(100\text{ m})^{-1}$ for Nigardsbreen and between -0.72 and +0.20 C $(100\text{ m})^{-1}$ for Storbreen (Fig. 3.1). Thus, the lapse rate difference between summer and winter is

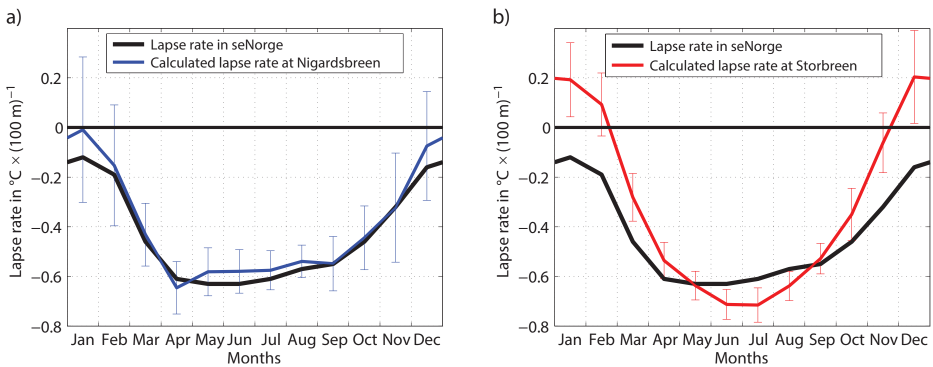

Figure 3.2: Comparison of the *seNorge* temperature lapse rate with the calculated lapse rate (with standard deviation) at the location of the AWS at Nigardsbreen (left) and Storbreen (right).

larger based on the measurements than the one used in *seNorge*. The positive lapse rates for Storbreen during winter indicate that temperature inversions are more common at Storbreen than in other parts of the country. Since air temperatures during winter are well below freezing point, the discrepancies during winter do not affect the usage of the temperature dataset for mass-balance modeling. Whereas at Nigardsbreen the lapse rates are in good agreement throughout the year, at Storbreen measured summer temperatures are lower than the extrapolated temperatures calculated by *seNorge*. However, this misfit on Storbreen might be caused by the location of the AWS on the glacier surface where temperature lapse rate are typically steeper (e.g. Petersen and others, 2013; Petersen and Pellicciotti, 2011) since near-surface air temperatures can be strongly affected by katabatic flow (Shea and Moore, 2010).

Compared with temperature, interpolating precipitation is more complicated as the distribution of precipitation is strongly influenced both by orography and distance to the sea. Therefore, a complex distribution of precipitation is typical for Norway. Moreover, 49 % of the land surface of Norway is situated above 500 m a.s.l., where only 16 % of the precipitation stations are located (Engelhardt and others, 2012). For spatial interpolation of precipitation in *seNorge* the observed precipitation is first corrected for systematic undercatch due to wind losses (Førland and others, 1996). The correction factor depends on the exposure to wind which is defined by the orographic characteristics at each station using the average and the lowest altitude within a 20 km radius around each station. The interpolation of the corrected precipitation for the areas between the stations is done by triangulation (Tveito and Førland, 1999; Tveito and others, 2000). The gridded daily precipitation values are extrapolated to the altitude of the respective *seNorge* model grid point, using a vertical precipitation gradient of 10 % per 100 m altitude below 1000 m a.s.l. and 5 % per 100 m altitude above 1000 m a.s.l. (Jansson and others, 2007).

The seNorge temperature and precipitation dataset was used to model the seasonal glacier mass balances for the glacierized area of mainland Norway (Article II, section 8.2). Using the vertical precipitation gradients as free parameters, the average gradients yielding the

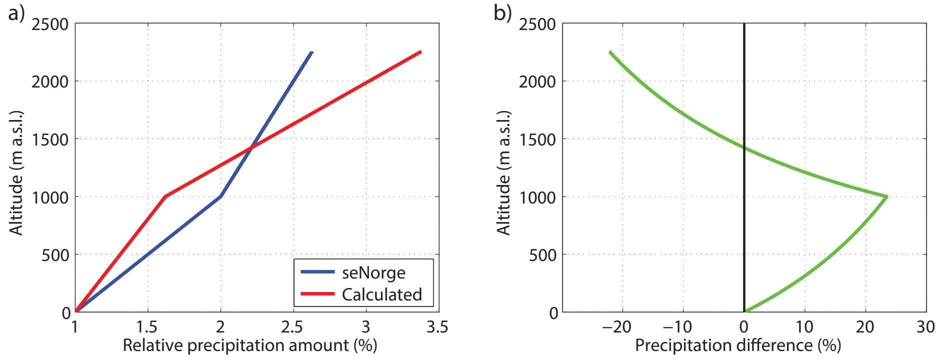

Figure 3.3: a) Precipitation gradient applied in *seNorge* compared to the calculated gradient that fits best to the measured winter mass balances. b) Relative difference between these two gradients.

best agreement to all measured winter glacier mass balances were 6.2 % per 100 m altitude below 1000 m a.s.l. and 14 % per 100 m altitude above 1000 m a.s.l., respectively. Compared to the applied gradients in *seNorge*, these gradients are lower below 1000 m a.s.l. and higher above (Fig. 3.3). This would imply that *seNorge* is on average overestimating precipitation in an altitudinal range up to 1500 m a.s.l. and underestimating above.

Temperature and precipitation are the most important variables controlling glacier mass balance. Many glacier studies interpolate temperature and precipitation measurements from a nearby weather station across the spatial extent of the glacier (e.g. Schuler and others, 2005). However, the large elevation gradient in many glacierized catchments leads to large variations in temperatures and precipitation across the glacier. As Gardner and Sharp (2009) pointed out, using temporal varying temperature lapse rates in a degree-day model improves modeling glacier mass balances rather than using a constant lapse rate. Another data source for temperature and precipitation data are downscaled re-analyzed climate model data (e.g. Schuler and others, 2008). However, proper simulation of the mass-balance evolution of a glacier requires much finer resolution for both temperature and precipitation than typical global or regional climate models can provide. Although both over- and underestimation of precipitation is occurring in the *seNorge* interpolation (e.g. Dyrrdal, 2010; Stranden, 2010; Engelhardt and others, 2012; Saloranta, 2012), the gridded data of *seNorge* are a valuable data source because of its high spatial resolution and availability for all of mainland Norway. Applications comprise permafrost studies (e.g. Gisnås and others, 2013; Westermann and others, 2013) and avalanche forecasting. For an overview of the interpolation scheme and cross validation of the *seNorge* temperature and precipitations data see Mohr and Tveito (2008), for detailed information on the interpolation methods, see the manual by Mohr (2008).

3.2 Applied glacier mass balance model

Distributed mass-balance modeling has become an important tool in glacier monitoring (e.g. Machguth and others, 2006). Modeling the annual surface mass balance of a glacier requires the calculation of both the winter and summer mass balances and includes mainly modeling the mass gain by snowfall and the mass loss by meltwater runoff.

The accumulation of snow is usually computed using a threshold temperature T_s below which all precipitation is assumed to fall as snow. This threshold temperature can be fixed or be surrounded by an interval ΔT where the precipitation P gradually changes from snow to rain (Auer Jr, 1974), depending on the air temperature T_a. Thus,

$$\text{Snow} = \begin{cases} P & \forall \quad T_a \leq T_s - \frac{\Delta T}{2} \\ P \cdot \left(\frac{T_s - T_a}{\Delta T} + 0.5 \right) & \forall \quad T_s - \frac{\Delta T}{2} < T_a < T_s + \frac{\Delta T}{2} \\ 0 & \forall \quad T_a \geq T_s + \frac{\Delta T}{2} \end{cases} . \tag{3.1}$$

A threshold temperature (T_s) distinguishes between rain and snow. This temperature is centered within an interval of 2 K where the precipitation linearly shifts from snow to rain. Spatial and temporal variation of these parameters occur and have been subject to several studies (e.g. Førland and Hanssen-Bauer, 2003; Kienzle, 2008).

The melt model used in this study (and in Article II and III) is a conceptual model that calculates daily melt rates of snow or ice $M_{\text{snow/ice}}$ by using a distributed temperature-index approach including potential solar radiation (e.g. Hock, 1999; Engelhardt and others, 2013b). For T_{sn} (*seNorge* air temperature) $>$ T_{m} (threshold temperature for melt), melt was calculated to

$$M_{\text{snow/firn/ice}} = (\Theta + R_{\text{snow/firn/ice}} \cdot I) \cdot (T_{\text{sn}} - T_{\text{m}}), \tag{3.2}$$

with the melt factor Θ, the radiation coefficients for snow, firn and ice $R_{\text{snow/firn/ice}}$ and the potential clear-sky solar radiation I.

Following the calculations of Funk and Hoelzle (1992), the potential radiation of a point at the surface can be calculated to

$$I = \int_{t_1}^{t_2} I_0 \cos(\vec{N}, \vec{S}) \mathrm{dt} \tag{3.3}$$

where t_1 and t_2 are the time of sunrise and sunset, respectively, I_0 the solar constant (1367 Wm^{-2}) and the vectors $\vec{N}$ and $\vec{S}$ oriented perpendicular to the surface and towards the sun, respectively. For the calculations, the slope and the aspect of the surface have to be considered, requiring a digital terrain model (DEM) with a preferably low horizontal grid resolution.

A DEM of 25 m resolution was used in order to calculate the potential solar radiation for the location of a sonic ranger in the ablation zone of Nigardsbreen (61.7 °N). The daily values of potential radiation are varying between 10 W m^{-2} in December and 345 W m^{-2} in June (Fig. 3.4, red line). Whereas most of the glacier surface is located on a plateau,

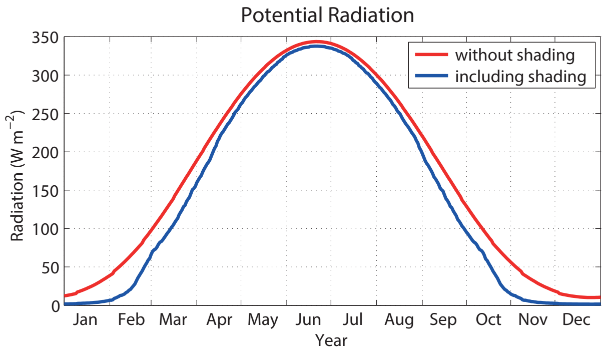

Figure 3.4: Daily average clear-sky short-wave radiation flux for the location of the sonic ranger on the glacier tongue of Nigardsbreen.

the glacier tongue is surrounded by steep mountains, shading the glacier surface from direct solar radiation for low solar angles. However, especially during the melt period this effect is quite small (Fig. 3.4, blue line). In addition, reflected radiation from the surrounded valley slopes further decrease this difference. Differences in potential solar radiation due to exposition or shading effects of surrounding slopes cannot be resolved appropriately with the grid resolution of the *seNorge* input data of 1 km. Thus, in the following calculations, daily averages of potential solar radiation are only dependent on the day of year and on latitude of the study point.

Melt rates of the sonic ranger are available during the melt season in 2011. It is assumed that only (glacier) ice was melting. Using the *seNorge* air temperature and precipitation data (further interpolated to the location of the sonic ranger), daily melt rates have been calculated using melt models of different complexities: (1) a classical degree-day model using only air temperature as input, (2) the conceptual model following equation 3.5, and (3) the conceptual model following equation 3.5 using measured incoming short-wave radiation instead of potential radiation. In model (1), the calibration of the free parameter is defined by the sum of the measured summer ablation. In model (2) and (3), the two free parameters are calibrated by both matching the sum of the measured summer ablation, and to reproduce variation in melt in order to minimize the root mean square error between measured and modeled melt.

The use of the potential solar radiation significantly enhances the model performance for both daily melt rates (Fig. 3.5a,b) and daily discharge rates (Hock, 1999, 2005). Using measured incoming short-wave radiation instead of potential radiation in equation 3.5 (Fig. 3.5c) leads to an improvement of modeling daily melt rates in about the same range as the improvement of using potential solar radiation compared to a simple degree-day model. However, the availability of short-wave radiation measurements is sparse. Since a temperature-index model using air temperature and potential solar radiation does not require additional measurements to a simple degree-day model, the use of such a model is recommended when besides temperature there are no additional data available for calculating melt.

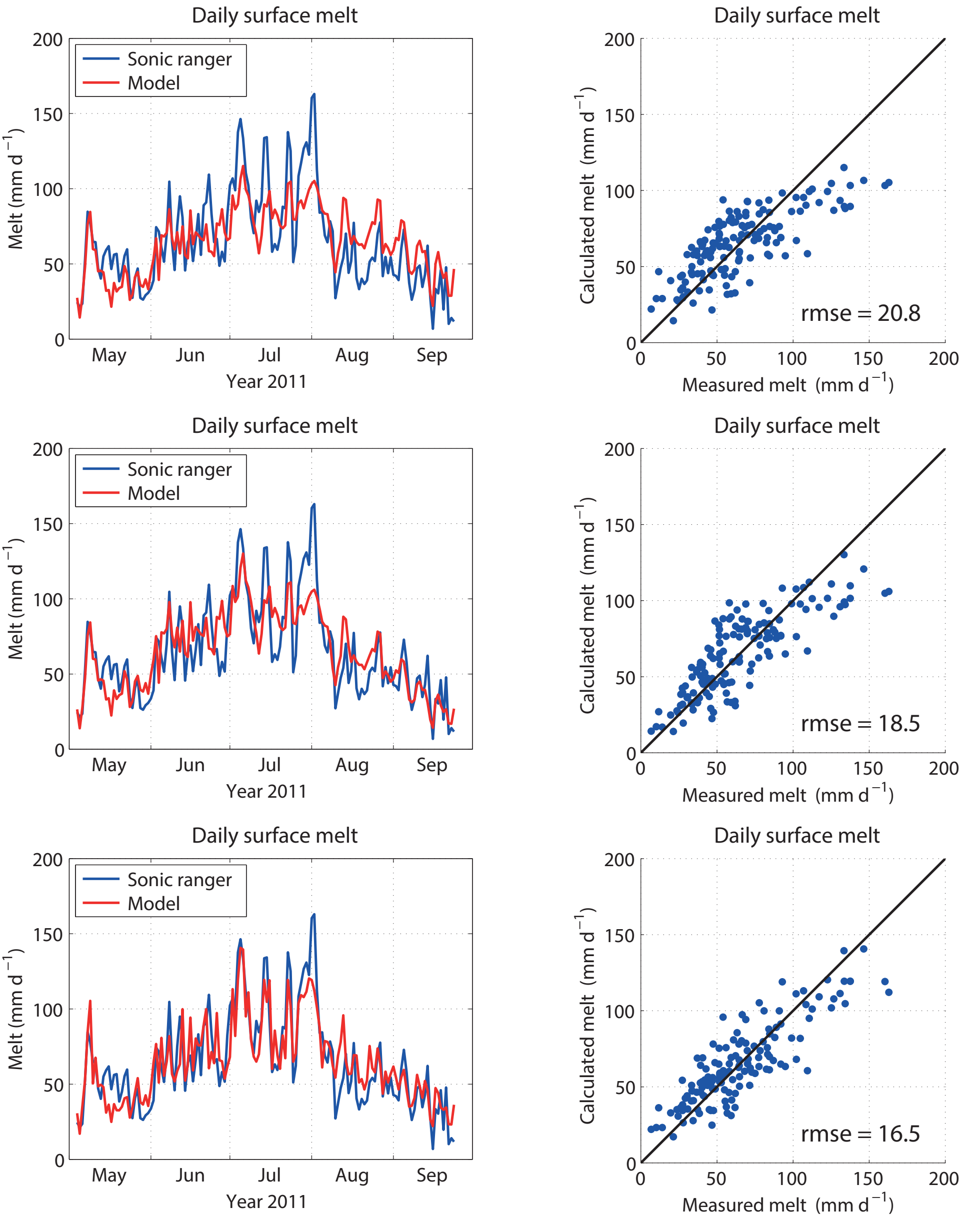

Figure 3.5: Measured and calculated daily melt rates at the glacier tongue of Nigardsbreen for the period 3 May – 23 September 2011. The calculations were performed with a temperature-index model using a) temperature only, b) temperature and potential solar radiation, and c) temperature and measured incoming short-wave radiation.

Due to different melt factors for snow and ice, it is important that the model correctly reproduces both the transition from melting snow to melting ice and the onset of a snow cover at the surface. The AWS on Storbreen includes a sonic ranger providing hourly melt rates (Andreassen and others, 2008). The albedo is defined as the ratio between the reflected and incoming short-wave radiation components. At the location of the AWS, high albedo values of > 80 % dominate (Fig. 3.6a). Such high albedo values are typical for fresh snow. The days with albedos from 60-80 % indicate snow during the melt period in early summer when due to wet snow the albedo is reduced. Only few days show albedos from 40-60 % which is typical for firn which does not occur in this part of the glacier. A secondary maximum of days is apparent for albedos of 30-35 % which is typical for ice. Comparing the albedo values based on measurements indicates a good model performance for this point location for the transitions between snow and ice.

Since the station has been relocated to the same (geographic) location several times, the sonic ranger measurements do not reflect the real surface elevation change, but the relative change in surface elevation. From 2001-2012 the surface at the AWS location decreased by about 25 m (Fig. 3.6b). The mass-balance model reproduces the annual accumulation and melt seasons. Discrepancies during the period with snow cover may result in assumptions of the snow density which was kept constant for during the model period. Nevertheless, the data gaps of the sonic ranger measurements can be filled by the model results. Since ablation can show large variation on small spatial scales (e.g. Sugiyama and others, 2011), model performance usually improves with increasing model domain by integrating over spatial variations in mass balances which can be induced by local effects like wind driven snow redistribution (Winstral and others, 2012).

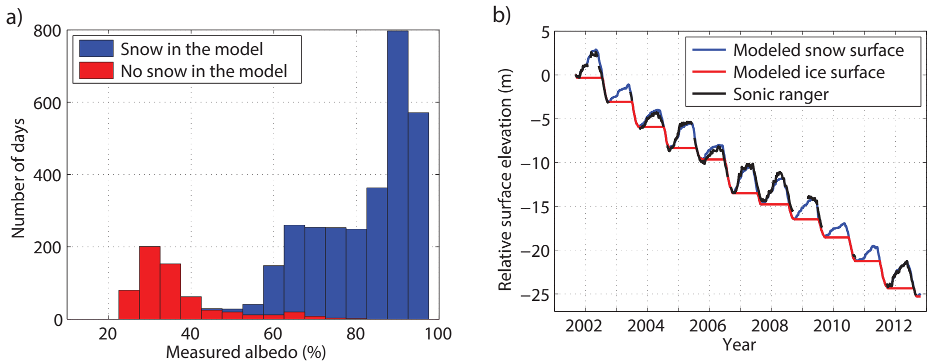

Figure 3.6: Model validation in the ablation zone of Storbreen with a) albedo measurements, and b) accumulated melt rates.

Chapter 4

Model results

4.1 Mass balance of Norwegian glaciers

The mass balance model from section 3.2 is applied to the glacierized area in mainland Norway. The optimization of the parameters uses all available seasonal mass balance data from the study period 1961-2010 (Kjøllmoen and others, 2011). The *seNorge* precipitation gradients were calibrated to best reproduce all available winter mass-balance measurements and the melt factor and the radiation coefficients were calibrated to best reproduce the summer mass-balance measurements. Since melt can also occur during the winter season and snowfall during the summer season, the seasonal parameters are not independent from each other and have to be optimized in an iterative process. With this parameter set (Tab. 4.1) the seasonal mass balances of the glacierized area are calculated for the study period 1961-2010 (Article II, section 8.2). Although this spatial averaged parameter set is less reliable for individual glaciers, the parameter set can also be used to extract seasonal mass balances for parts of the glacierized area.

The largest glacier in continental Europe is Jostedalsbreen. With an area of 475.8 km^2 (Andreassen and others, 2012b) it is accounting for about 18 % of the glacierized area in mainland Norway. On Jostedalsbreen, seasonal mass balance measurements are currently only carried out on the outlet glacier Nigardsbreen which is located on the eastern side of Jostedalsbreen and which comprises about 10 % of its surface (Fig. 4.1). Instead of extrapolating the measurements from Nigardsbreen to the whole of Jostedalsbreen, the parameter set can be used to model the seasonal mass balances of Jostedalsbreen. Both, Jostedalsbreen and Nigardsbreen are well represented by the applied model in terms of area and elevation (Tab. 4.2). The area of Jostedalsbreen did not change much during the last decades. Earlier surveys reported an area of 487 km^2 in 1984 (Østrem and others, 1988) and 473 km^2 in 1945 (Liestøl, 1962).

The modeled seasonal and annual mass balances of Jostedalsbreen yields for the study period 1961-2010 an average winter balance of +2.7 m w.e. and an average summer balance of -2.4 m w.e. (Fig. 4.3). The annual balance was thus slightly positive (+0.3 m w.e.) but annual values vary between -2.3 and +3.1 m w.e. The standard deviations are 0.8 m w.e. for both the winter and summer mass balances and 1.5 m w.e. for the annual balances. Although year-to-year variability is large, winter balances were highest during the study period between 1981-2000 and lowest in the 1960s. Summer balances

Table 4.1: Applied parameter set in the model which is optimized to all measured seasonal mass-balances (mb) in mainland Norway.

Parameter	Description	Value	Unit	optimized to
RC_{snow}	Radiation coefficient for snow	11	mm K^{-1} d^{-1} kW^{-1} m^{2}	summer mb
RC_{ice}	Radiation coefficient for ice	15	mm K^{-1} d^{-1} kW^{-1} m^{2}	summer mb
MC	Melt coefficient	1.4	mm K^{-1} d^{-1}	summer mb
p_1	Precipitation gradient ($\leq$ 1000 m)	6.2	% (100 m)$^{-1}$	winter mb
p_2	Precipitation gradient (> 1000 m)	14	% (100 m)$^{-1}$	winter mb

were most negative after 2000. The accumulated mass balance over this period is 15 m w.e. (Fig. 4.4). Whereas the glacier was close to balance in the 1960s, positive annual balances prevailed from 1971-2000. After 2000, the annual mass balances were mostly negative, leading to a decrease of the accumulated mass balance of 7 m within 10 years.

The outlet glacier Nigardsbreen shows a similar course of the accumulated mass balance as whole Jostedalsbreen. However, annual mass balances were on average 0.2 m w.e. lower at Nigardsbreen which can be explained by its location on the eastern side of Jostedalsbreen and therefore leeward side of the maintain ridge. The accumulated mass balance of 6 m w.e. at Nigardsbreen is lower than annual performed stake measurements suggest (Kjøllmoen and others, 2011). However, geodetic measurements indicate an overestimation of the mass-balance measurements at Nigardsbreen with an accumulated mass balance close to zero between the years 1984 and 2010 (Bjarne Kjøllmoen, personal communication).

Table 4.2: Comparison of the glacier inventory of Jostedalsbreen (Andreassen and others, 2012b) and Nigardsbreen (Kjøllmoen and others, 2011) with the corresponding data in the 1 km model resolution.

	Jostedalsbreen		Nigardsbreen	
	Inventory	Model	Inventory	Model
Area (km^2)	473.8	474	47.2	49
Highest elevation (m a.s.l.)	2008	1900	1946	1890
Median elevation (m a.s.l.)	1596	1600	1616	1610
Average elevation (m a.s.l.)	1554	1534	1564	1544
Lowest elevation (m a.s.l.)	345	433	345	433

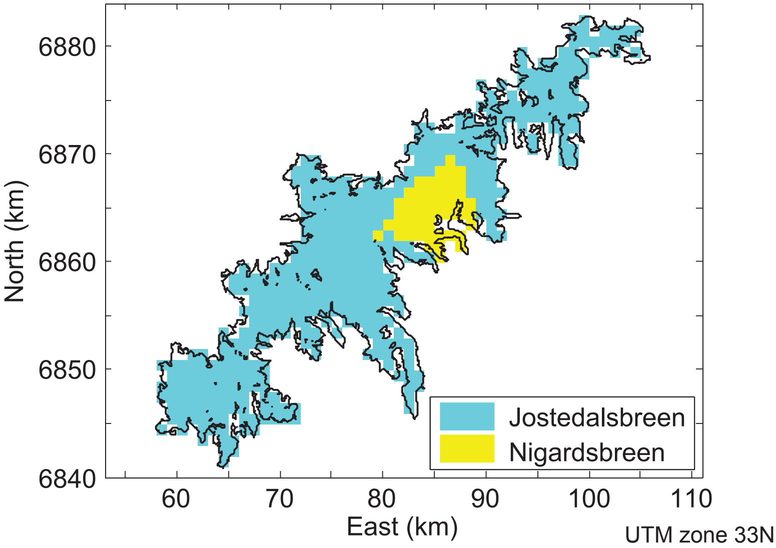

Figure 4.1: Outline of Jostedalsbreen (black line) and 1 km grid resolution as represented in *seNorge*. The outlet glacier Nigardsbreen is highlighted.

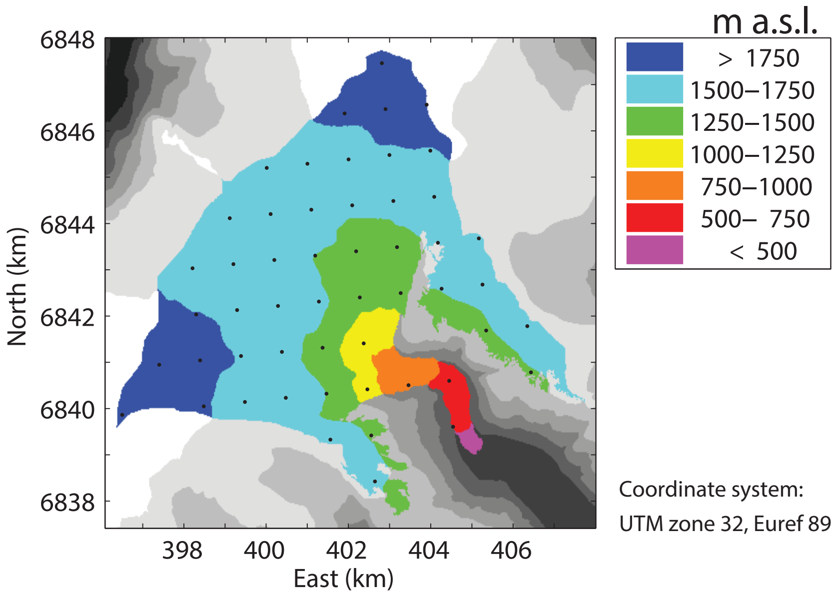

Figure 4.2: Elevation of Nigardsbreen. The black dots indicate the location of the *seNorge* grid points.

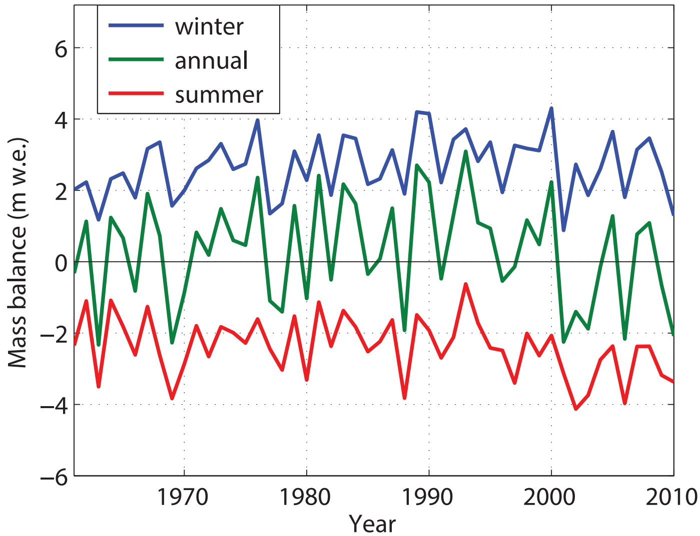

Figure 4.3: Modeled seasonal and annual mass balances of Jostedalsbreen for the study period 1961-2010.

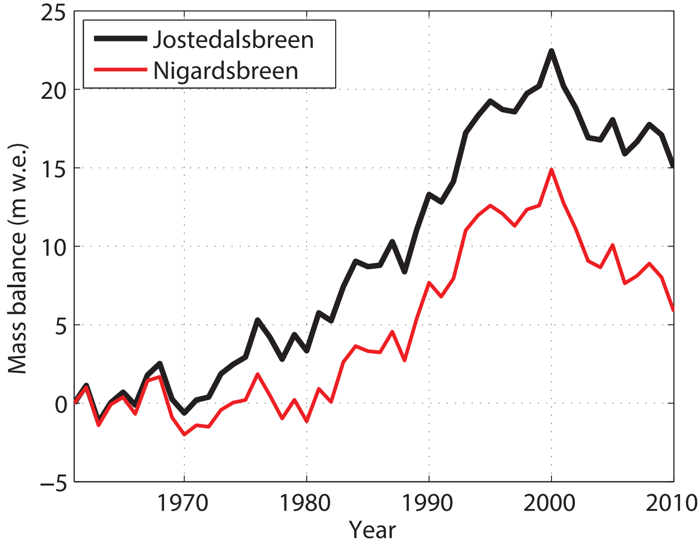

Figure 4.4: Modeled cumulative mass balances of Jostedalsbreen and Nigardsbreen for the study period 1961-2010.

4.2 Mass-balance sensitivity to climate variations

The seasonal and annual mass balances of a glacier present a large year-to-year variability (e.g. Fig. 4.3). In order to look closer on the driving factors of this variability, this section evaluates the sensitivity of modeled mass balance to perturbations in temperature and precipitation for five selected glaciers in Norway (Engabreen, Ålfotbreen, Nigardsbreen, Storbreen and Rembesdalsskåka). The glaciers are chosen because of long time series of available mass-balance measurements and their spatial distribution within Norway (Fig. 2.1). In contrast to the previous section, where an average parameter set was applied to the glacierized surface of mainland Norway, here the mass balance model was individually adjusted to the each glacier by minimizing the root mean square error (rmse) between measured and modeled seasonal mass balances. Following Oerlemans and others (1998), the climate sensitivities of the annual glacier mass balance b_n to variations in temperature and precipitation, C_T and C_P, can be defined to

$$C_T(1\ K) = \frac{\mid b_n(+1\ K) - b_n(-1\ K) \mid}{2}\ ;\ C_P(10\ \%) = \frac{\mid b_n(+10\ \%) - b_n(-10\ \%) \mid}{2}. \quad (4.1)$$

These sensitivities represent so called static sensitivities as they do not include dynamic responses of the glacier like an area change to variations in mass balances. In addition, model parameters like threshold temperatures or melt coefficients are kept constant. Larger precipitation changes would be accompanied by different meteorological conditions like cloud cover or wind speed and thus affect several terms in the energy balance although air temperature remains unchanged. Therefore, the climate sensitivities represent idealistic values to (relatively) small input changes.

To calculate the climate sensitivities, all temperature and precipitations values of the model period (1957-2012) were changed individually. The impact on the mean annual mass balance was evaluated for the study period 1961-2012 (Tab. 4.3). The values correspond well with results of similar studies from different glaciers in Norway (e.g. Schuler and others, 2005; Andreassen and Oerlemans, 2009; DeWoul and Hock, 2005; Rasmussen and Conway, 2005). Ålfotbreen, the most maritime glacier in the study, shows largest sensitivity to both temperature and precipitation changes. With 1.74 m w.e. K^{-1}, the temperature sensitivity of Ålfotbreen is about twice as large as for Engabreen, Nigardsbreen and Rembesdalsskåka, and more than three times as large as for Storbreen. Though less pronounced, the sensitivity to precipitation changes is also largest at Ålfotbreen.

Table 4.3: Mean annual air temperature T_a and precipitation sum P_a together with their standard deviations (σ_T/σ_P) from *seNorge* and climate sensitivity for 1961-2012 using perturbations in mean annual air temperature (C_T) and precipitation sum (C_P).

Glacier	T_a (°C)	σ_T (K)	P_a (m)	σ_P (%)	C_T (1 K) (m w.e.)	C_P(10 %) (m w.e.)	C_P(30 %) (m w.e.)
Engabreen	-1.9	1.0	4.4	24	0.92	0.35	1.06
Ålfotbreen	0.5	0.7	6.2	23	1.74	0.46	1.39
Nigardsbreen	-2.1	0.7	3.4	21	0.86	0.27	0.80
Storbreen	-5.0	0.9	1.6	14	0.55	0.17	0.50
Rembesdalsskåka	-2.9	0.9	2.2	23	0.79	0.26	0.78

Although located in different regions of Norway (Fig. 2.1), Engabreen, Nigardsbreen and Rembesdalsskåka show quite similar temperature and precipitation sensitivities with values between 0.79 and 0.92 m w.e. K^{-1} and 0.26 and 0.35 m w.e. $(10\ \%)^{-1}$, respectively. However, the elevation range of Rembesdalsskåka is with 845 m (Tab. 2.1) much smaller than for Engabreen (1485 m) and Nigardsbreen (1642 m). As a consequence, the dynamic response to climate changes is expected to be smaller since a rise of the ELA would faster surpass the maximal glacier elevation. For Hardangerjøkulen of which Rembesdalsskåka is an outlet, Giesen and Oerlemans (2010) showed that the annual mass balance becomes negative at all elevations and disappears by the end of the 21st century assuming a linear temperature increase of 3 K during this period. Storbreen is the glacier situated in the most continental climate in this study and the only glacier with a negative mean annual mass balance during the study period. Here, the sensitivities to changes in both temperature (0.55 m w.e. K^{-1}) and precipitation (0.17 m w.e. $(10\ \%)^{-1}$) are smallest.

In addition to fixed changes for the climate sensitivities, the mean annual mass balance was calculated for the study period 1961-2012 with varying input of temperature and precipitation. The range for these variations is ± 3 K for temperature and ± 30 % for precipitation values. The impact on annual glacier mass balance by changes in meteorological input parameters is not surprising a negative correlation with changes in mean annual air temperature and a positive correlation with changes in mean annual precipitation sums (Fig. 4.5). For higher temperatures, the sensitivity to temperature changes increases, whereas the sensitivity to precipitation changes decreases. This is mainly due to a prolongation of the melt season and to a lesser extend due to a shift of precipitation from snow to rain. However, with increasing temperature perturbations, the sensitivities are less reliable as dynamic reactions of the glaciers would strongly alter the values. Differences between the five studied glaciers occur in the magnitude of these correlations and the range of how much precipitation change compensates the effect of temperature increase or decrease. For Engabreen a change of 1 K in annual air temperature would be compensated by a respective change of 26 % of the annual precipitation sum. For all other glaciers, a corresponding precipitation change would be >30 % (Tab. 4.3).

More important than changes in annual air temperature and precipitations sums are changes in seasonal variations of temperature and precipitation. Generally, temperature affects the glacier mass balance during the ablation period and precipitation during the accumulation period. Temperature also affects the winter balance through the snow/rain threshold temperature T_s. Higher temperatures shorten the accumulation period and therefore the amount of precipitation falling as snow. This effect is most pronounced in late spring and early fall, when temperatures on the glaciers are close to freezing point and precipitations frequently shift between rain and snow. In addition, temperature changes are negligible during winter. The influence of precipitation on the summer balance is generally small. However, glacier ice covered by fresh snow from cold weather events almost shuts down melt due to the high albedo (Oerlemans, 2004; Brock and others, 2000). An increase in winter precipitation also affects the summer balance through prolongation of the snowmelt period and therefore the onset of the more efficient melt of firn or ice.

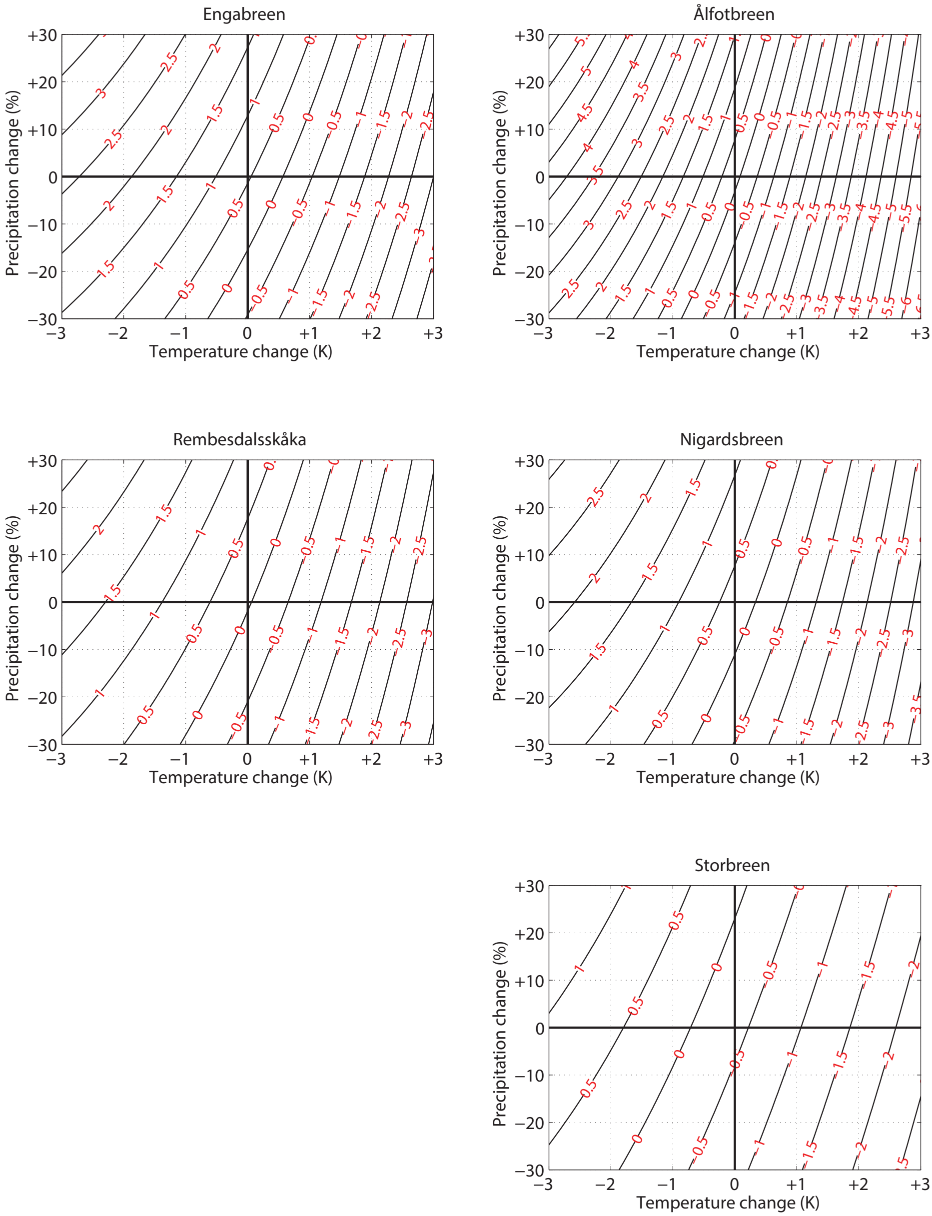

Figure 4.5: Sensitivity of annual mass balance to changes in annual temperature and precipitation for the study period 1961-2012.

For the five study glaciers in Norway, the sensitivity of winter mass balances (wb) and summer mass balances (sb) to a rise of monthly temperature (T_m) by 1 K and a rise of monthly precipitation (P_m) by 30 % was tested. Although many previous studies used a rise of monthly precipitation of 10 % (e.g. DeWoul and Hock, 2005; Andreassen and others, 2006), a rise of 30 % was chosen for this study, sice it has about the same impact on annual mass balance as a temperature rise of 1 K (see e.g. Andreassen and Oerlemans, 2009). At the five glaciers, all mentioned effects can be distinguished. As for the annual sensitivities, the monthly sensitivities for the glaciers Engabreen, Nigardsbreen and Rembesdalsskåka are most similar among the studied glaciers (Fig. 4.6). The higher sensitivity at Engabreen to temperature which was found for the annual values is limited to the months May to October. For the months June to August this is due to a higher melt sensitivity. In May, September and October, Engabreen shows a higher sensitivity of the winter balance to temperature changes. For the same months, Engabreen also shows a slightly higher sensitivity to precipitation changes than the other two glaciers.

Ålfotbreen shows the largest sensitivity to both annual temperature and precipitation of all five study glaciers. However, for the monthly sensitivities, the dominant sensitivity is restricted to the months from November through April. During this period, the mean precipitation sum for Ålfotbreen is about 80 % than for Nigardsbreen (Fig. 4.7), the closest glacier to Ålfotbreen within this study. Although precipitation values are also higher during summer on Ålfotbreen than on Nigardsbreen, the higher air temperatures on Ålfotbreen make it less likely for the precipitation during summer to fall as snow. The sensitivity of a rise in precipitation to summer mass balances on Ålfotbreen is therefore similar to this sensitivity on Nigardsbreen and even lower than for the other three glaciers.

In contrast to precipitation, the sensitivity of glacier mass balance to a rise in temperature is highest on Ålfotbreen for all months. The higher air temperatures on Ålfotbreen yield not only the highest melt efficiency, but also the highest sensitivity to summer mass balance during the summer months. The most striking results for Ålfotbreen are the extreme high temperature sensitivities to winter mass balance for the period September through January compared to all other glaciers. This can be explained by the high precipitation values and relatively high air temperatures during this period (Fig. 4.7). The temperatures are close to the snow/rain threshold temperature which makes a little increase in temperature a lot of precipitation falling as rain instead of snow and the winter balance becoming smaller. Thus, the mass balance sensitivity to a rise in temperature is highest in September when temperature sensitivities of both summer and winter balances are large on Ålfotbreen.

For Storbreen the mass balance sensitivity is lowest for both temperature and precipitation. The sensitivity tests to monthly changes reveal that there are no changes in glacier mass balance by temperature variation between November and March. This is due to low air temperatures that remain below freezing point even with 1 K higher monthly temperatures. In addition, the mass balance sensitivity to a temperature rise in summer is smaller than for the other study glacier. Also at Storbreen, changes in winter precipitation affect the annual mass balance more than during summer. However, the sensitivity of precipitation variations shows smallest variations throughout the year.

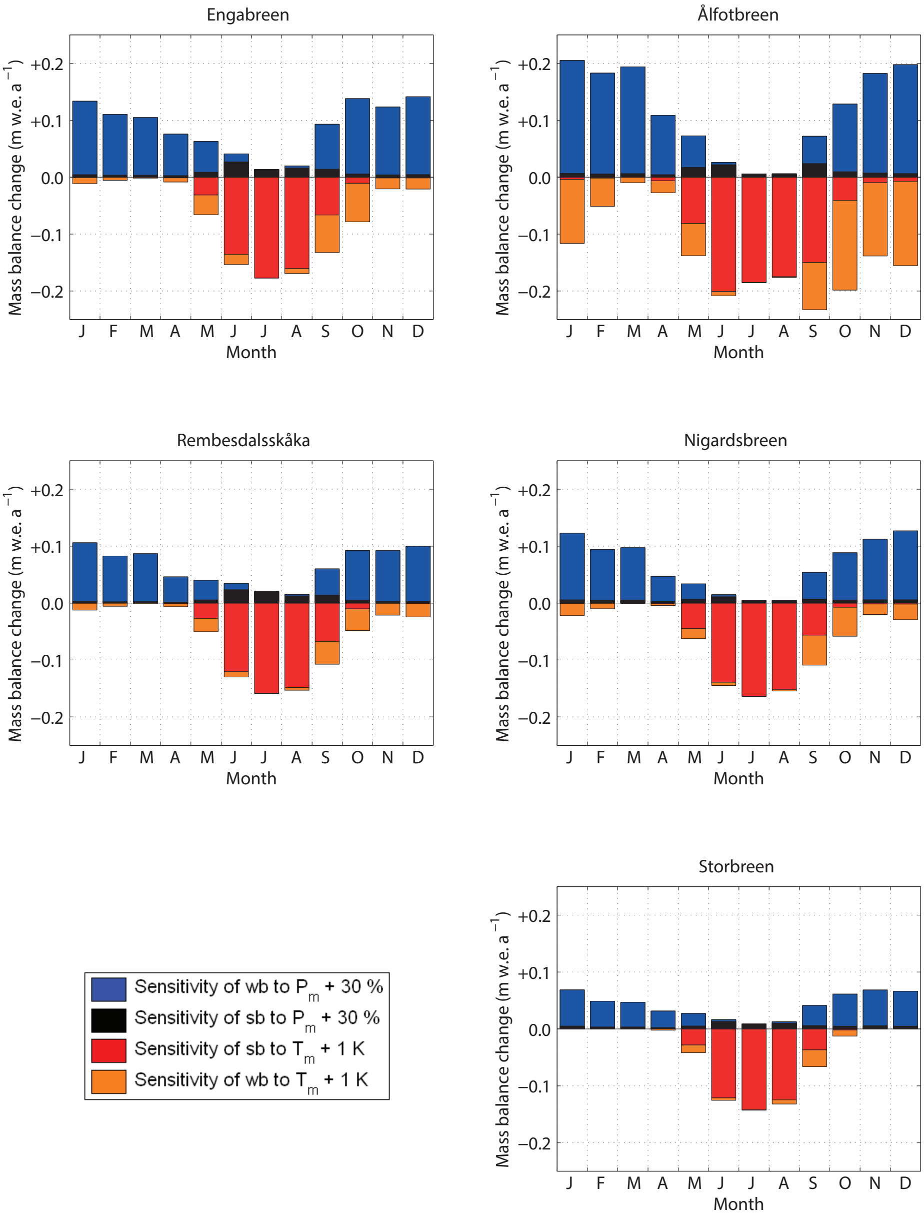

Figure 4.6: Sensitivity of winter mass balances (wb) and summer mass balances (sb) to a rise of monthly temperature (T_m) by 1 K and a rise of monthly precipitation (P_m) by 30 % for the study period 1961-2012.

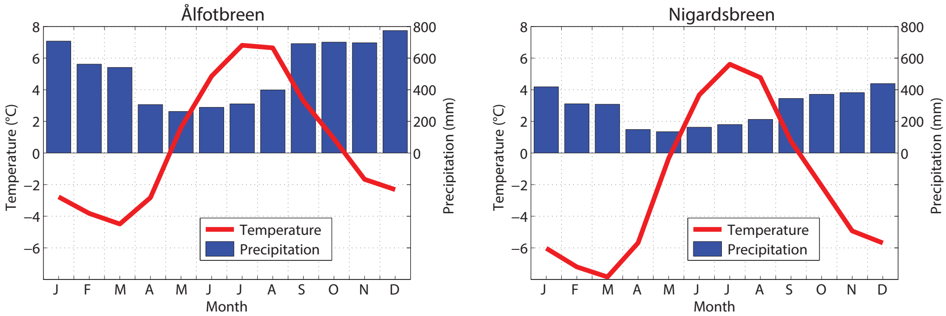

Figure 4.7: Climograph of Ålfotbreen and Nigardsbreen from *seNorge* data (1961-2012).

To conclude it was found that Ålfotbreen, the most maritime glacier in this study shows largest mass balance sensitivities to both temperature and precipitation variations, whereas these sensitivities are smallest at Storbreen, the most continental glacier in this study. The remaining three glaciers Engabreen, Nigardsbreen and Rembesdalsskåka show similar mass balance sensitivities, yet with Engabreen showing slightly larger and Rembesdalsskåka showing slightly less mass-balance sensitivities than Nigardsbreen.

4.3 Discharge contribution from Norwegian glaciers

Glaciers and their future changes have a large impact on the runoff from glacierized catchments (e.g. Huss and others, 2008b). Depending on the percentage of glacier cover within a catchment, the same changes in temperature and precipitation can have contrasting effects on the runoff regime (Dahlke and others, 2012). With increased glacierization within a catchment, discharge is less dependent on precipitation changes, but more on changes in air temperature (e.g. Braun and others, 2000).

The annual discharge sum for the catchment of Nigardsbreen in western Norway increased over the last decades (Fig. 4.8). This increase is most pronounced in the 2000s, with discharge values that were about 30 % higher than in the preceding decades (e.g. Engelhardt and others, 2013a). The increase in precipitation in Norway in the years 1985 to 1995, which can be attributed to higher values of the North Atlantic Oscillation (NAO) index (Hurrell, 1995), had therefore no noticeable effect on the discharge from the catchment of Nigardsbreen in this period. Large amounts of snow during winter can even reduce meltwater production during summer by shortening the period of bare ice on the glacier which has higher melt efficiency than snow. The following increase in discharge was mainly due to increased summer air temperature (see Article III, chapter 8.3).

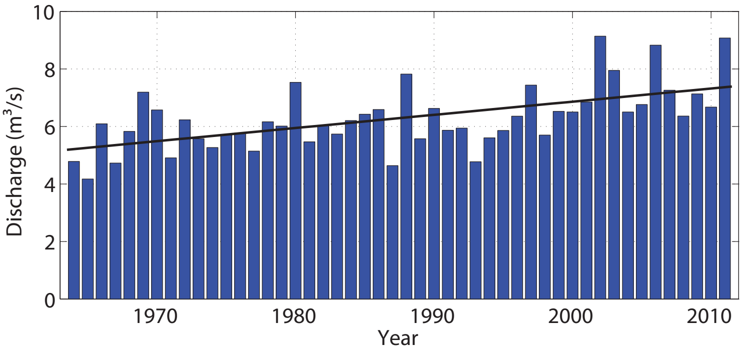

Figure 4.8: Measured discharge from the catchments of Nigardsbreen with linear interpolation (black line).

The mass-balance model described in section 3.2 also allows meltwater analysis by calculating the melt components snow-, firn- and ice melt. The components firn- and ice melt are hereinafter summed up and referred to as glacier melt. Discharge measurements are available for the catchments of Ålfotbreen, Nigardsbreen and Storbreen (Fig. 4.9). The catchments, for which these measurements are performed, also include areas outside the glaciers but the glacierized parts in these catchments is between 51 and 72 % (Tab. 4.4).

The specific discharge (i.e the annual discharge sum divide by the catchment size) from the three catchments follows the precipitation gradient in Western Norway from west to east with average values of 5.8 m a^{-1} for Ålfotbreen, 2.8 m a^{-1} for Nigardsbreen and 1.9 m a^{-1} for Storbreen (Fig. 4.10). On a horizontal distance of about 80 km from Ålfotbreen to Nigardsbreen, the specific discharge is reduced by more than 50 %. A further reduction

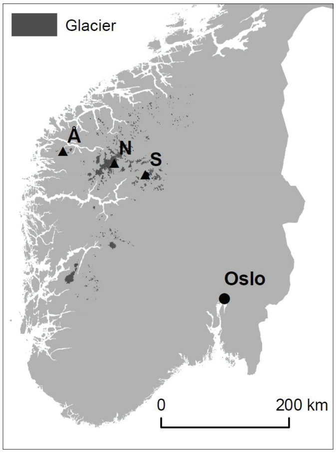

Figure 4.9: Location of the study sites Ålfotbreen (Å), Nigardsbreen (N) and Storbreen (S) within the glacierized areas in southern Norway.

Table 4.4: Overview of the three study catchments.

	Ålfotbreen	Nigardsbreen	Storbreen
Catchment size (km^2)	8.3	66	8.0
Glacier coverage (%)	51	72	65
Latitude (°N)	61.8	61.7	61.6
Longitude (°E)	5.6	7.1	8.1
Mean catchment elevation (m a.s.l.)	927	1401	1597
Start of mass balance measurements	1963	1962	1949
Start of discharge measurements	1994	1962	2010

of about 30 % is visible from Nigardsbreen to Storbreen, situated about 55 km further to the east. Although the absolute year-to-year variability is highest at Ålfotbreen, due to the higher absolute discharge values the coefficient of variation c_v is slightly higher at Storbreen (c_v = 0.18) than at Ålfotbreen (c_v = 0.16), and lowest at Nigardsbreen (c_v = 0.12). The temporal analysis of the specific discharge for the study period 1961-2012 reveals for all catchments the lowest discharge values for the 1960s. The specific discharge at Ålfotbreen is highest in the 1980s and peaks in the years 1989 and 1990 with values close to 8 m a^{-1}. This maximum is also visible but much less pronounced at Nigardsbreen and completely absent at Storbreen. For both of these two catchments, the decade with the highest specific discharge is 2002-2011.

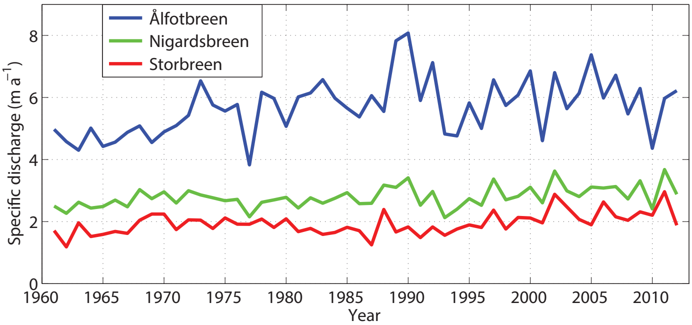

Figure 4.10: Modeled specific discharge from for the catchments of Ålfotbreen, Nigardsbreen and Storbreen for the study period 1961-2012.

The relation between specific discharge and both mean annual air temperature and precipitation sum shows that discharge at Ålfotbreen is mainly precipitation driven, whereas discharge at Nigardsbreen and Storbreen is mainly temperature driven. Despite differences in glacierization and the different catchment sizes, the climatic forcing outranges all other influencing effects on the discharge for these three catchments (see also Article III, section 8.3).

Analyzing the distribution of the discharge throughout the year (averaged for the study period 1961-2012) reveals that the highest discharge rates for all three catchments are in July (Fig. 4.11) and the lowest in March (no substantial discharge is modeled at Storbreen between November and April). The discharge is split up into the components rain (liquid precipitation), glacier melt and snowmelt; the latter further divided into snowmelt from snow from the glacierized and the non-glacierized parts of the catchment. Snowmelt is the largest contributor to discharge for all catchments with more than 50 % of the annual discharge sum. The distribution between snowmelt from glacierized and non-glacierized parts of the catchments approximately reflects the glacier coverage within the catchment. The snowmelt of the non-glacierized areas peaks in June at Ålfotbreen and Nigardsbreen and is slightly higher in July at Storbreen. For all catchments, snowmelt from the glacier area is highest in July and most glacier melt is observed in August. The specific discharge originating from glacier melt is similar for the three catchments; however, its relative contribution is increasing from Ålfotbreen to Storbreen (i.e. from west to east) as total

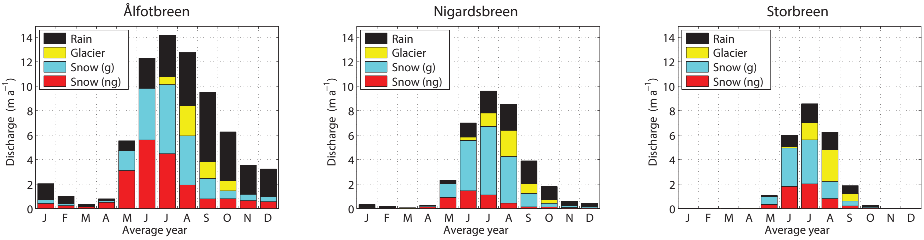

Figure 4.11: Monthly average of the specific discharge (1961-2012). The discharge is split up into the contributing source of rain, glacier melt and snowmelt. The latter is further split up into snowmelt from the glacierized (g) and non-glacierized (ng) areas.

specific discharge decreases. The contribution of rain to discharge is decreasing from west to east. Whereas at Storbreen, more than 80 % of the discharge originates from melt, at Ålfotbreen higher temperature and precipitation values lead to relatively high total discharge rates in fall and winter (Fig. 4.11).

The relative contribution of glacier melt to total discharge is on average between 8 % at Ålfotbreen, 13 % at Nigardsbreen and 20 % at Storbreen. However, a large year-to-year variability is visible where glacier contributions varies between 0 and 52 % (Fig. 4.12). During the decade from 1991-2000 glacier contribution was lowest at all catchments. Most remarkably are the 7 years between 1989 and 1995, when at Ålfotbreen only about 1 % of the discharge originated in glacier melt. In these years, Ålfotbreen experiences a series of years with positive annual mass balances that were on average +1.6 m w.e. a^{-1} (e.g. Kjøllmoen and others, 2011). After the year 2000 the contribution from glacier meltwater to discharge increased and the decade from 2001-2010 yields the highest glacier contribution for all catchments. Together with the relative increase in glacier contribution, the year-to-year variability increased.

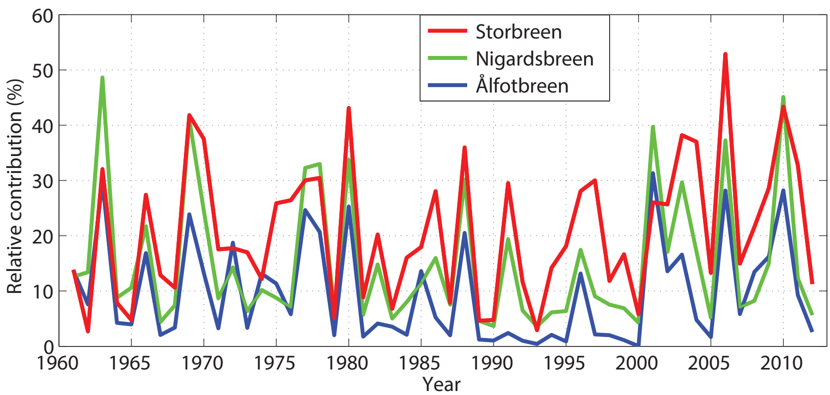

Figure 4.12: Relative annual glacier meltwater contribution to discharge from the catchments of Ålfotbreen, Nigardsbreen and Storbreen during the study period 1961-2012.

The relation between glacier melt contribution to discharge and total discharge is contrasting. Whereas at Ålfotbreen years with low glacier melt coincide with high total discharge, at Storbreen glacier melt and total discharge are positively correlated (Fig. 4.13). No correlation between these values is found at Nigardsbreen. Ålfotbreen is the westernmost catchment and therefore the climate is most maritime (Fig. 4.7). The discharge is mainly dependent on snowmelt and rain. Large amounts of snow during winter reduce the period of bare ice on the glacier. Additionally, large amounts of snow from the non-glacierized parts of the catchments are available for melt and discharge. As rain is a larger contributor to discharge than glacier melt in all months (Fig. 4.11), cool and rainy years add preferably to discharge than warm and dry years which are yielding more glacier melt. At Storbreen, the contribution of glacier melt is exceeding the contribution from rain during the glacier melt season (July-September). Therefore, the importance of summer temperatures in addition to annual precipitation is becoming more dominant from Ålfotbreen towards the more continental glacier at Storbreen.

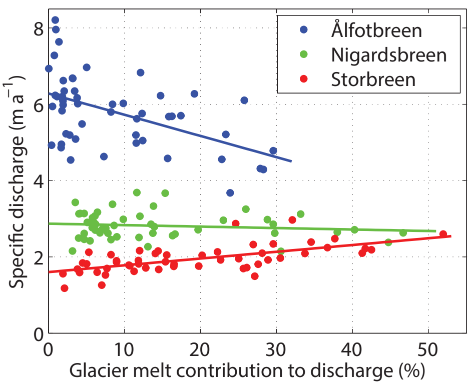

Figure 4.13: Relationship between annual glacier meltwater contribution and annual specific discharge from the catchments of Ålfotbreen, Nigardsbreen and Storbreen. Each dot represent one year for the study period 1961-2012; in addition, a linear interpolation is plotted.

4.4 Discharge sensitivity to climate variations

The previous section revealed the large year-to-year variability of specific discharge (Fig. 4.10), the even larger variability of glacier melt contribution to discharge (Fig. 4.12) and the contrasting correlation of glacier melt contribution to total discharge (Fig. 4.13). This section deals with the sensitivity of annual discharge to changes in annual and monthly temperature and precipitation changes for the same three catchments as in the previous section (Ålfotbreen, Nigardsbreen and Storbreen).

As revealed in section 3.2, temperature and precipitation rise can compensate each other to a certain degree in terms of annual glacier mass balance. In contrast, both temperature and precipitation rise lead to increased total discharge. An increase of the mean annual air temperature by 1 K leads to an increase of the annual discharge sum by 20-24 % (Fig. 4.14, left panel). However, a temperature decrease in the same range only reduces the discharge by 14-19 %. This asymmetry in sensitivity to temperature is strongest at Nigardsbreen. Here, a temperature increase by 3 K is supposed to almost double the discharge. The asymmetric discharge sensitivity to temperature at Nigardsbreen, which is much smaller at the other two catchments, can be explained by the hypsometry of the glacier. At Nigardsbreen, the average ELA (equilibrium line altitude) for the period 1962-2010 is 1500 m a.s.l. (Kjøllmoen and others, 2011). A rise in the ELA of 200 m surpasses the plateau of the glacier and doubles the ablation area (Fig. 4.2). Measurements showed than in the years 2001-2010, the mean ELA was about 100 m higher than in the years 1962-2000. Considering the same periods, the discharge increased by 25 % (Fig 4.8).

Whereas for the annual mass balances, a precipitation increase by 30 % would approximately compensate a temperature increase by 1 K, the combination of such temperature and precipitation changes would lead to an discharge increase of 31-38 %. However for discharge, a precipitation decrease of 30 % would balance a temperature increase of 1 K at Ålfotbreen and a temperature increase of 0.5 K at Nigardsbreen and Storbreen. Whereas a precipitation change by 30 % leads to an discharge change by about 10 % at Nigardsbreen and Storbreen, this impact is about twice as large at Ålfotbreen, where the discharge contribution of rain and snow in non-glacierized areas is higher than at the other two catchments.

In order to study the discharge sensitivity to monthly changes in meteorological input, an individual increase of the mean monthly air temperature by 1 K and a decrease of the monthly precipitation by 30 % was performed (Fig. 4.14, right panel). At all catchments, the discharge sensitivity to temperature is similar to the mass balance sensitivity. The sensitivity is smallest in March, which also is the coldest month at Ålfotbreen and Nigardsbreen (Fig. 4.7). At Storbreen, due to low temperatures, a temperature increase by 1 K between November an March has no influence on discharge. Whereas at Ålfotbreen, the discharge sensitivity to temperature quite similar between May and December, at Nigardsbreen and Storbreen there is a clear discharge sensitivity to a temperature rise in the months June to September. The discharge sensitivity to a decrease in precipitation by 30 % is at Ålfotbreen largest from August to December, when both precipitation and contribution of rain to discharge are high. The compensation of a 1 K warming and a 30 % less precipitation for discharge at Ålfotbreen is not only valid for annual means,

but also for most of the months. A larger impact of such a precipitation change is visible for late winter/ early spring and a larger impact of such a temperature change in late spring/ early summer. At Nigardsbreen the discharge sensitivity to precipitation changes is largest in summer and early fall with a maximum in August. At Storbreen the sensitivity to precipitation is even further narrowed down to the three summer months.
Although catchment size and glacierization is similar for Ålfotbreen and Storbreen, the difference in climatic conditions yield strong differences in both mass-balance and discharge sensitivities to changes in meteorological input. Nigardsbreen, which is both geographically and climatically between the other two catchments, shows sensitivities that are also between the ones of the other catchments. However, due to its geometry and large glacier size, it may yield the largest discharge increase when the ongoing temperature rise continues.

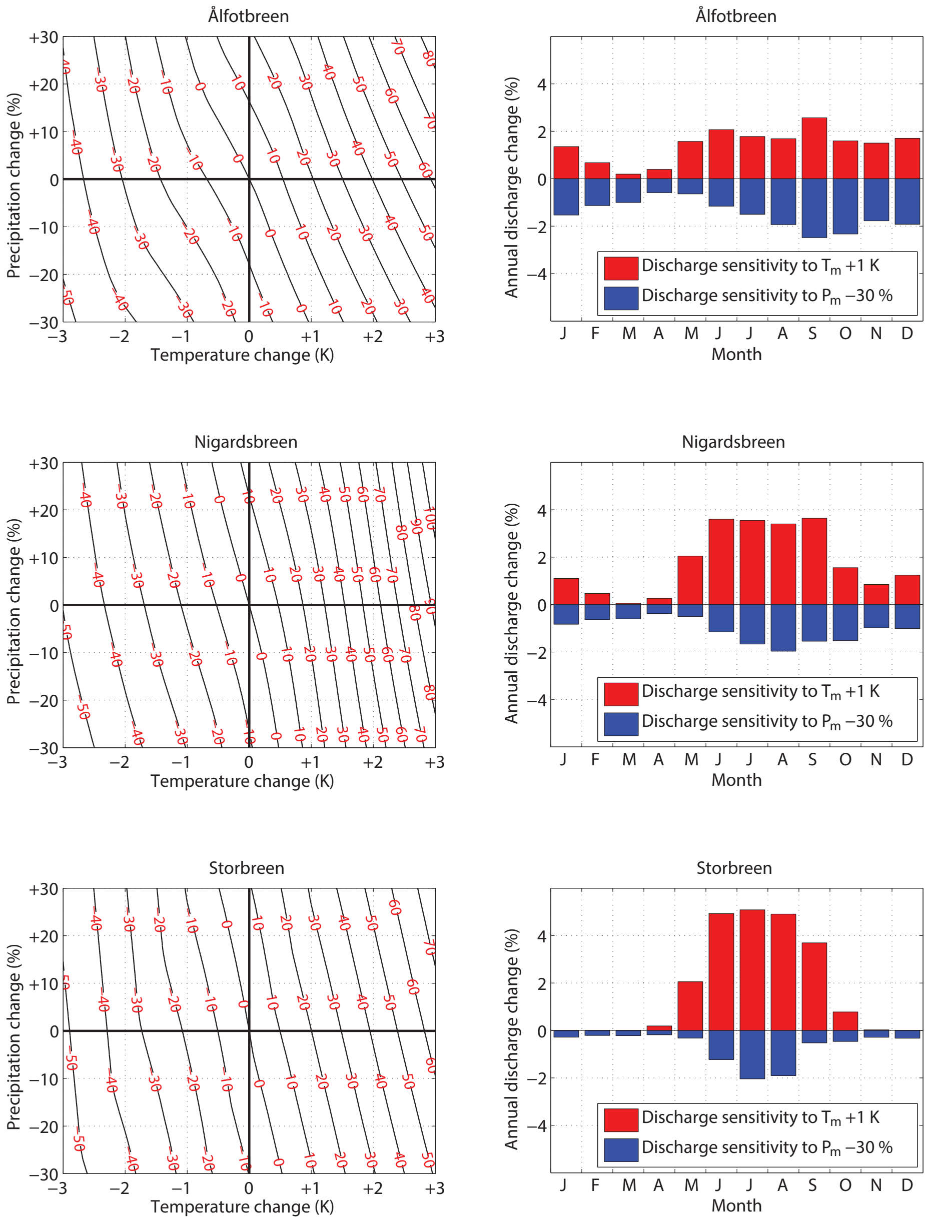

Figure 4.14: Left: Sensitivity of annual discharge to changes in annual temperature and precipitation. Right: Sensitivity of annual discharge to a change of monthly temperature (T_m) by 1 K and a change of monthly precipitation (P_m) by 30 %. All data are averaged for the study period 1961-2012.

Chapter 5

Summary of research articles

5.1 Evaluation of *seNorge* precipitation data

The article is a case study that evaluates the precipitation products from *seNorge* with glacier mass balance measurements. The service *seNorge* provides gridded temperature and precipitation for mainland Norway on a 1×1 km horizontal grid (section 3.1). The products are based on station measurements using a gridding algorithm for horizontal interpolation and vertical extrapolation. Precipitation measurements by rain gauges are predominantly performed in populated areas located at lower elevations such as coastal areas and valleys. Therefore, there are large uncertainties in estimating precipitation for higher altitudes where typically very few measurements are available. The uncertainties are predicated on both the horizontal interpolation and the vertical extrapolation of measurements due to sparsity of observations as well as the large spatial variability of precipitation in mountainous regions.

The study is a kind of inverse approach by evaluating the gridded precipitation with local measurements at high elevations that are not included in the gridding algorithm. These measurements are winter mass-balances at stake locations on five glaciers in Norway (Fig. 2.1) covering different glacier sizes and climate conditions. Using gridded temperature and precipitation data from *seNorge*, the surface glacier mass balance was modeled for each stake location on all five glaciers by interpolating the four closest *seNorge* grid data to these locations. The model accounts for accumulation of snow, melting of snow and ice by applying a degree-day approach and considers refreezing assuming a snow depth dependent storage.

The results reveal that the precipitation grids in *seNorge* provide a reasonable estimate of precipitation in high mountainous areas. On average for each glacier, modeled and measured surface mass-balance evolutions agree well. Glacier wide averages show good agreement between modeled winter mass balance and stake measurements. However, the comparison of point values at individual stake locations show large variability. The main differences between model results and measurements can be attributed to shortcomings in spatial resolution of the *seNorge* grid. The 1 km^2 resolution is not able to capture spatial mass-balance variability at smaller scales. The limitation of the *seNorge* data in describing the local accumulation characteristics is clearly visible at Storbreen (5.4 km^2), where the maximal horizontal distance between the seven evaluated stakes is 2.2 km.

Further sources of uncertainty in the gridded data are the fixed precipitation gradients that can result in both large over- and underestimation when extrapolating precipitation to high elevations. A significant increase of the bias between model and observations with altitude at Rembesdalsskåka, situated on the western side of Hardangerjøkulen, suggests that orographic enhancement of precipitation on the windward side of the ice cap is not appropriately captured by the stations in the vicinity and thus not included in the gridding algorithm of *seNorge*. The closest precipitation station of the glacier is located on the north-eastern side of the ice cap which is probably more shaded for precipitation than Rembesdalsskåka on the western side. Therefore, the orographic precipitation increase is apparently higher than suggested by *seNorge*. The incorporation of wind-direction dependent lee effects by using locally adapted precipitation gradients for precipitation could probably improve the performance of *seNorge* in this area.

The main result from this study is that the gridded data from *seNorge* can be used to calculate mass balance for glaciers in mainland Norway. However, further adjustments of the precipitation data are necessary to provide a more robust input data set. This can be achieved by using different precipitation gradients (as used in Article II) or by a precipitation correction factor for each glacier (as used in Article III).

5.2 Glacier mass balance of Norway from 1961-2010

The study aims to investigate the spatial and temporal distribution of the reference glacier mass balance of mainland Norway for the study period 1961-2010 using a distributed temperature-index mass-balance model including potential direct solar radiation (section 3.2). The model is driven by gridded datasets of temperature and precipitation from *seNorge* in a horizontal resolution of 1 km. Model parameters are calibrated and validated using the extensive dataset of direct glacier mass-balance measurements for winter and summer balances of Norwegian glaciers (e.g. Kjøllmoen and others, 2011).

Glacier mass balance measurements are only available for 42 glaciers in Norway. Long-term mass balance measurements of more than 20 years even exist for only 10 glaciers. However, the study of Rasmussen and Conway (2005) showed that in Norway there is a strong positive correlation of seasonal balances from one glacier to other nearby glaciers and that the vertical gradients of seasonal mass balances are close to linear. Therefore, there is a high transferability of the existing measurements to other glaciers in Norway.

Driven by *seNorge* data, the calibrated model provides for the first time a complete overview of spatial averaged seasonal glacier mass balances from 1961-2010 for all of mainland Norway. This model approach is useful to give an overview of both temporal and spatial variability of glacier mass balance since glacier monitoring covers only a small part of the glacierized area and has irregular temporal coverage. The results may be used to assess spatial patterns of mass balance in the study period and may also be used for to hydrological applications. For smaller regions, locally adjusted parameter sets may be more appropriate.

In this study, the precipitation input from *seNorge* is corrected by applying precipitation gradients that yield agreement between averaged modeled and observed winter mass balance. The melt parameters in the model (one melt factor and two radiation coefficients) are optimized to the corresponding summer balance. Modeled seasonal and annual glacier mass balances for Norway for the study period 1961-2010 reveal a large year-to-year variability. Nevertheless, winter and annual mass balance show positive trends between 1961 and 2000 followed by a remarkable decrease in both summer and winter balances between 2000 and 2010. The resulting annual mass balance of close to -1 m w.e. a^{-1} for the first decade of the 21st century might only be a glimpse of what can be expected for the future.

5.3 Contribution of snow and glacier melt to discharge

In this study, daily discharge series are modeled for three highly glacierized catchments in Norway for the study period 1961-2012 and annual and monthly contributions of snowmelt, glacier melt and rain to streamflow are quantified.

Glacierized catchments significantly alter the streamflow regime due to snow and glacier meltwater contribution to discharge. In this study, the distributed temperature-index mass-balance model (section 3.2) is applied to three different highly glacierized catchments (>50 % glacier cover) in Norway. The spatial pattern of the catchments follows a gradient in climate continentality from west to east. The model calculates the seasonal mass balances and daily discharge rates for the study period 1961-2012. The time series of modeled annual discharge are split up in their contributing water sources snowmelt, glacier melt and rain. Both the annual discharge and the discharge components are used to examine changes in the runoff regimes by analyzing spatial variations and temporal evolution.

The model uses the daily gridded temperature and precipitation values from *seNorge* as input. For each catchment an individual precipitation correction factor is applied to fulfill the water balance over the period of available discharge data. The model accounts for accumulation of snow, transformation of snow to firn and ice, evaporation and melt. The model was calibrated for each catchment based on measurements of seasonal glacier mass-balances and daily discharge rates. For validation, daily melt rates were compared with measurements from sonic rangers located in the ablation zones of two of the glaciers and an uncertainty analysis was assessed for the third catchment.

The model simulations reveal an increase of the relative contribution from glacier melt for the three catchments from less than 10 % in the early 1990s to 15-30 % in the late 2000s. The decline in precipitation by 10-20 % in the same period was therefore overcompensated resulting in an increase of the annual discharge by 5-20 %. Changes in these contributing sources were much larger than the variations in annual discharge sums. Annual discharge sums and annual glacier melt are strongest correlated with annual and winter precipitation at the most maritime glacier and, with increased climate continentality, variations in both glacier melt contribution and annual discharge are becoming stronger correlated with variations in summer temperatures. Differences between the catchments can be attributed to the increasing climate continentality from west to east rather than differences in catchment size or glacier coverage. Discharge from the most maritime catchment is most sensitive to changes in precipitation whereas discharge at the most continental catchment is most sensitive to changes in summer temperatures. Especially for the latter, glacier melt is a large contributor to discharge in late summer which may lead to reduced discharge in this time of the year when its glacier area decreases.

5.4 Glacio-hydrological modeling for Beas river basin, Northern India

In this study, the distributed temperature-index mass-balance model (section 3.2) is implemented in a large scale hydrological model calculating the discharge for the Beas River basin, Northern India. The main aim of the study is to evaluate re-analyzed and satellite-based precipitation datasets in driving a large scale glacio-hydrological model for this basin. In addition, the glaciological model is used to model the average annual contribution of glacier- and snowmelt to streamflow.

Precipitation is the most critical input for any hydrological models. Gridded precipitation are available for India by the satellite-based dataset from the *Tropical Rainfall Measuring Mission* (TRMM) (Huffman and others, 2007) and the *WATCH Forcing Data* (WFD), developed by the *Water and Global Change* (WATCH) project (Weedon and others, 2010) which consists of meteorological variables derived from ERA-40 reanalysis (Uppala and others, 2005). The spatial and temporal distribution of these gridded precipitation datasets in India is compared with rain gauge measurements by statistical analyses. Then, with all three precipitation datasets, discharge is simulated for the Beas River basin, a mountainous region in northern India for the period 1997-2001. The glacio-hydrological discharge model is based on the *water and snow balance modelling system* (WASMOD), which has been adjusted to macro scales (WASMOD-D) (e.g. Gong and others, 2009) and enlarged by a glacier mass-balance module. The glacier module is applied on the grid cells representing areas of glacier cover. Information of glacierization is based on the Global Land Ice Measurements from Space (GLIMS) Glacier Database (http://glims.colorado.edu/glacierdata/glacierdata.php) (e.g. Raup and others, 2007). The model results are compared and assessed based on Nash-Sutcliffe efficiency and relative volume error.

The average annual precipitation in India (1997-2001) from TRMM is in general less than that from WFD, especially in the mountainous regions of northern India. More remarkable differences exist in the variances than in the mean values. Modeling discharge for the Beas River basin during the period 1997-2001, the global gridded satellite-based dataset performs on average as well as the sparse rain gauge data in this region. The satellite-based rainfall dataset performs slightly better than the re-analyzed dataset. The application of the glacio-hydrological model in the basin based on the three datasets produced satisfactory results with model performances in terms of Nash-Sutcliffe efficiency coefficients around 0.7 and < 5 % volume error.

The results indicate that the global satellite-based dataset might be considered as a potential data source for water resources estimates by driving large-scale hydrological models in small basins where the availability of ground-based measurements is poor. The average annual contribution of glacier- and snowmelt to streamflow from the basin during the period 1997-2001 is calculated to 2.56 km^3 a^{-1} accounting for 41 % of the total discharge sum. The results of this study may also be useful for estimating the impact of climate change on hydrological response in other basins in Northern India.

Chapter 6

Conclusions and outlook

The main goal of this thesis was to give a spatially and temporal complete overview of mass balance situation of Norwegian glaciers and the meltwater contributions to discharge during the past 50 years. In addition, temporal and spatial mass-balance and discharge variabilities were revealed and sensitivities to temperature and precipitation changes analyzed.

The applied temperature-index model was driven by gridded temperature and precipitation data from *seNorge* as input. These data were evaluated and found suitable as input for mass-balance modeling (Article I). However, different vertical gradients were applied for modeling the mass balance of the glacierized area in Norway (Article II) and a constant correction factor was applied for each of the catchment for which discharge was investigated (Article III). The model was also implemented in a large-scale hydrological model for a river basin in northern India (Article IV) where different precipitation datasets were evaluated in their performance in modeling discharge.

Hock and others (2005) found that for otherwise similar climate conditions, discharge is positively correlated with temperature and negatively correlated with precipitation with increasing glacierization. However, for the glaciers in southern Norway discharge becomes positively correlated with temperature and negatively correlated with precipitation with increasing continentality from west towards east.

Modeling glacier mass balance is still a challenge with various error sources that have to be considered. Daily resolution of meteorological input data does not account for the daily temperature cycle. This cycle can lead to melt during the day, although daily mean temperature is below freezing point.

With accelerated climate changes, glacier changes and their influence on streamflow will become of increasing importance in those parts of the world where rivers are highly influenced by meltwater from glacierized catchments. Studying changes in glacier mass balance and discharge characteristics for future climate conditions can also be achieved by using climate model data of a regional climate model. In order to extrapolate the applied model into the future, a reduction of the glacierized area has to be accounted for when enhanced glacier melt has caused glacier volume to decrease significantly. The adjustment of the glacier area to different climate conditions can be calculated using a flowline model (e.g.

Laumann and Nesje, 2009b) or by simple volume-area scaling. Another use of such a model could be the evaluation discharge in higher temporal resolution of daily discharge and serve hydropower applications.

The main conclusion is that mass-balance and hydrological models do not have to be complex to produce reasonable results when the spatial and temporal scale is large enough. A simple temperature-index model works well for many mass balance and discharge applications. However, on smaller scales and detailed process studies, more complex models are necessary in order to account of physical processes. For mass-balance modeling, increased model complexity would be the use of an energy-balance model rather than a temperature-index model which require input data that are expensive to measure and therefore rarely available. The limitations in modeling are therefore either the lack of suitable input data or the lack of spatial or temporal model resolution. The trade-off between model complexity and available data remains one of the fundamental constraints in describing nature.

Chapter 7

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Chapter 8

Articles

8.1 Article I

– **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2012): Evaluation of gridded precipitation for Norway using glacier mass-balance measurements. – *Geografiska Annaler. Series A, Physical Geography* **94**: 501–509, DOI: 10.1111/j.1468-0459.2012.00473.x.

8.2 Article II

– **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2013): Glacier mass balance of Norway from 1961-2010 calculated by a temperature-index model. – *Annals of Glaciology* **54**(63): 32–40, DOI: 10.3189/2013AoG63A245.

Annals of Glaciology 54(63) 2013 10.3189/2013AoG63A245

Glacier mass balance of Norway 1961–2010 calculated by a temperature-index model

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ABSTRACT. Glacier mass balance in Norway is only observed over a small portion (≤15%) of the glacierized surface and only for short time periods (≤10 years) for most sites. To provide a comprehensive overview of the temporal mass-balance evolution, we modeled surface mass balance for the glacierized area of mainland Norway from 1961 to 2010. The model is forced by operationally gridded daily temperature and precipitation fields which are available at 1 km horizontal resolution from 1957 until the present. The applied mass-balance model accounts for melting of snow and ice by using a distributed temperature-index approach. The precipitation input is corrected to obtain agreement between modeled and observed winter mass balance, and a melt factor and two radiation coefficients are optimized to the corresponding summer balance. The model results show positive trends of winter balance between 1961 and 2000 followed by a remarkable decrease in both summer and winter balances which resulted in an average annual balance of -0.86 ± 0.15 m w.e. a^{-1} between 2000 and 2010 after four decades of zero to slightly positive annual mass balances.

INTRODUCTION

Glaciers and their snow cover represent storage of water over a wide range of timescales (e.g. Jansson and others, 2003). Changes in glacier mass balance may have great effects on streamflow both in annual volume (e.g. Huss and others, 2008; Farinotti and others, 2012) and in magnitude of melt-water floods (e.g. Nolin and others, 2010; Jost and others, 2011). Therefore, monitoring of glaciers is relevant to water resource management such as water supply or the operation of hydroelectric facilities (e.g. Hock and others, 2005). As glaciers are very sensitive to climate variations (e.g. Kaser and others, 2006), climate change is expected to have a major influence not only on ice volume but also on associated meltwater discharge both in magnitude and seasonality (e.g. Dahlke and others, 2012), and knowledge of mass balance is crucial for hydrologic modelling of glacierized catchments (e.g. Schaefli and Huss, 2011). However, many records of glacier measurements are quite short and cover only a small part of the glacierized area as extensive field measurements are expensive and labor-intensive (Braithwaite, 2002). Glacier mass-balance changes over long time-spans can be determined, for example, from surface elevation changes using laser scanning (e.g. Geist and others, 2005) or aerial photography (e.g. Kääb, 2000; Haug and others, 2009). To fill the gaps in determining mass balance at the regional scale and at high temporal resolution, previous studies have either extrapolated available measurements (e.g. Huss, 2012) or used mass-balance models of different complexities (for a review see Hock, 2005). For the latter, approaches range from simple temperature-index models (e.g. Johannesson and others, 1995) to complex surface energy-balance models (e.g. Hock and Holmgren, 2005). The required input for those models ranges from measurements at a nearby weather station to output of regional climate models (Machguth and others, 2009). However, the requirement of temporally and spatially distributed input data is often a limiting factor for mass-balance modelling over long time-spans (Andreassen and Oerlemans, 2009) or over large areas.

In mainland Norway, glacier mass balance is especially important for the country's hydropower potential as well as an indicator of climate variations. Measurements of glacier mass balance have been carried out on more than 40 glaciers, with the oldest and longest continuous series starting in 1949 (Andreassen and others, 2005). The results are published annually (e.g. Kjøllmoen and others, 2011) in reports of the Norwegian Water Resources and Energy Directorate (NVE). Although many glaciers are measured, the records are not able to show a complete picture of the temporal and spatial variability. Some studies have attempted to fill the gaps by the reconstruction of mass-balance data using upper-air meteorological data (e.g. Rasmussen and others, 2007; Andreassen and others, 2012a).

The aim of this study is to provide an overview of the temporal evolution of glacier mass balance in mainland Norway. Therefore, we used the operationally gridded temperature and precipitation datasets from seNorge and a distributed temperature-index approach including potential direct solar radiation (Hock, 1999) in order to model the mass balance of the glacierized surface of Norway for the period 1961–2010.

MASS-BALANCE DATA

The total glacierized area in mainland Norway (Fig. 1) is 2693 km^2 (Andreassen and others, 2012b), of which 92% is located between 800 and 1900 m a.s.l. (Fig. 2a). It comprises glaciers of different types and sizes; common types are ice caps, valley glaciers and cirque glaciers. The climate conditions vary significantly over the country not only in terms of temperature and precipitation, but also in terms of potential solar radiation given the large range in latitude (59.7–70.5° N).

Mass-balance measurements have been performed in Norway since 1949, starting on Storbreen, a glacier in the Jotunheimen mountain massif in central-southern Norway. Over the period 1961–2010, mass-balance measurements

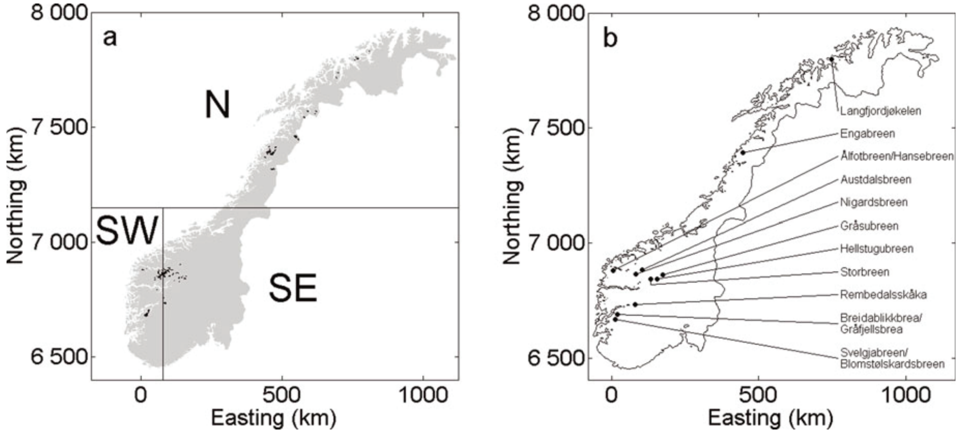

Fig. 1. (a) Glacierized area of mainland Norway divided into three regions, north (N), southwest (SW) and southeast (SE), with each having about equal areas of glacierized surface. Coordinates are given in Universal transverse Mercator (UTM) grid zone 33. Data source: Statens kartverk (the Norwegian Mapping Authority). (b) Position of mass-balance measurements with >10 years time series.

have been performed on a total of 42 glaciers in mainland Norway (Kjøllmoen and others, 2011). In 2010, mass-balance measurements were performed on 15 glaciers with a total glacier area of 191 km^2 and representing ~7% of the glacierized area in mainland Norway. Comparing the hypsometric distribution of the surveyed glaciers with that of the total glacierized area reveals that the surveyed glaciers span a representative range of altitudes (Fig. 2). However, the available mass-balance records are biased towards glaciers selected for hydrologic reasons, i.e. demands for development and operation of hydroelectric power stations. Therefore, many mass-balance datasets are quite short, covering only a few years. Measurements have never been carried out at more than 17 glaciers during the same year, and the corresponding glacier area for which mass-balance data are available varies since 1964 between 1, 20 and 250 km^2 (Fig. 3) representing 5–10% of the total glacierized area. The number of surveyed glaciers displays a maximum during the International Hydrological Decade (1965–74) and an increasing trend after a minimum in the early 1980s. A detailed overview of all glacier mass-balance measurements for the period 1949–2003 together with characteristics of the surveyed glaciers is given by Andreassen and others (2005).

The reported annual glacier-wide mass balances are derived by hypsometric integration of separate measurements of winter and summer mass balances at each glacier. The winter balance is obtained by measuring the bulk snow density and probing the snow depth along different profiles in order to capture spatial accumulation patterns. Stake readings and snow coring are used to confirm the probing. The summer balance is obtained from measurements at a network of stakes. The annual balance is calculated as the sum of the winter and summer mass balance. In this study we used the seasonal glacier-wide mass balances of the surveyed glacier area for model parameter calibration.

METHODS

In 2003, the Norwegian Meteorological Institute, NVE and the Norwegian Mapping Authority (Statens kartverk)

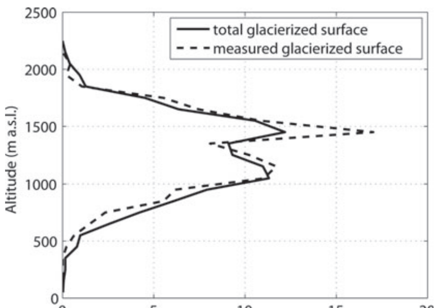

Fig. 2. Hypsometry of the glacierized area in Norway and of the area where glacier mass-balance measurements were carried out in 2010, based on the seNorge grid altitudes.

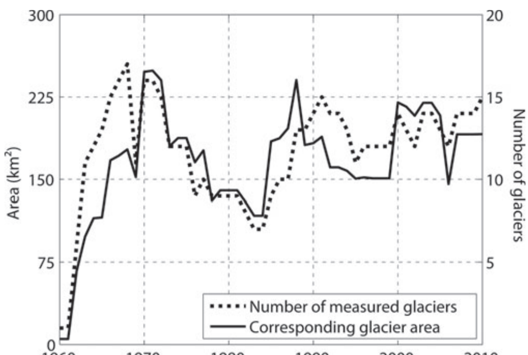

Fig. 3. Number and corresponding area of glaciers where mass-balance measurements were carried out between 1961 and 2010. Data source: NVE.

Table 1. Applied parameter set in the model that is optimized to all measured mass-balance series in mainland Norway

Parameter	Description	Value	Unit	Optimized to
RC_{snow}	Radiation coefficient for snow	11	$mm\,K^{-1}\,d^{-1}\,kW^{-1}\,m^2$	summer mass balance
RC_{ice}	Radiation coefficient for ice	15	$mm\,K^{-1}\,d^{-1}\,kW^{-1}\,m^2$	summer mass balance
MF	Melt factor	1.4	$mm\,K^{-1}\,d^{-1}$	summer mass balance
p_1	Precipitation gradient ($H \leq 1000$ m)	6.2	$\%\,(100\,m)^{-1}$	winter mass balance
p_2	Precipitation gradient ($H > 1000$ m)	14	$\%\,(100\,m)^{-1}$	winter mass balance

launched the service seNorge (Norwegian for 'See Norway'), which provides gridded meteorological and hydrological information for mainland Norway on its website (http://senorge.no). The temperature and precipitation fields are interpolated from available station measurements. In the present version (v.1.1) of seNorge, gridded products of daily (06.00 to 06.00 UTC) meteorological and hydrological fields at 1 km horizontal resolution are available for all of mainland Norway. The grids have been generated for the period from 1957 to the present and are regularly updated. Derived quantities such as snow depth, snow water equivalent or snowmelt are determined by a degree-day model (Engeset and others, 2004). A detailed review of the interpolation methods of temperature and precipitation is provided by Mohr (2008). Despite some weaknesses with the precipitation inter- and extrapolation in the mountainous regions, different evaluation studies found the gridded data of seNorge to be valuable, especially due to their high spatial resolution (Mohr, 2009; Dyrrdal, 2010; Engelhardt and others, 2012; Saloranta, 2012).

To calculate mass balances for the glacierized area of Norway, a model was set up using the gridded temperature and precipitation data from seNorge as input. The glacier outlines are available as shapefiles based on aerial photography from the Norwegian Mapping Authority. The outlines were intersected with the seNorge grid, and the model was run at daily time-steps for these glacier gridpoints for the period of available seNorge data (1957–2010). Changes of the individual glacier areas during the model period were not accounted for. Precipitation was accumulated as snow when the air temperature was below the threshold temperature for snowfall (T_s). According to observations by Auer (1974), the probability of snow occurrence is ~50% at a temperature of 2°C. We adopt this threshold and apply a transition interval (1°C, 3°C) where the precipitation shifts linearly from snow to rain. Daily melt M of snow or ice was calculated when the air temperature was above the threshold temperature for melt ($T_m = 0°C$) using a distributed temperature-index approach including potential direct solar radiation (see Hock, 1999):

$$M_{snow/ice} = \max\left[(\mathrm{MF} + \mathrm{RC}_{snow/ice} I)(T_{sn} - T_m), 0\right], \quad (1)$$

with the melt factor MF, the radiation coefficients RC for snow and ice, the potential direct solar radiation I and the seNorge air temperature T_{sn}. Differences in potential solar radiation due to exposition or shading effects of surrounding slopes were not accounted for as the grid resolution of 1 km would not resolve such phenomena appropriately. However, since potential solar radiation depends first of all on latitude, the use of radiation coefficients is a way to account for latitudinal differences in melt energy along the large north–south extent of Norway. To retrieve seasonal mass balances from the diurnal mass-balance series, we defined the start and the end of each season as the day when the glacier-wide mass balance was at its annual maximum (end of winter) or at its minimum (end of summer). To build up reasonable snow cover on the glacier surface, we used the period 1957–60 as model spin-up time and excluded it from the calibration and validation periods.

The winter mass balance is mainly dependent on precipitation. In seNorge, the measured precipitation values are interpolated to the grid at sea level using triangulation (Jansson and others, 2007) and adjusted to the respective seNorge grid altitude using vertical precipitation gradients of $p_1 = 10\%\,(100\,m\,a.s.l.)^{-1}$ for elevations $H \leq 1000$ m a.s.l. and $p_2 = 5\%\,(100\,m\,a.s.l.)^{-1}$ for $H > 1000$ m a.s.l. (Jansson and others, 2007). Previous validation studies evaluated seNorge precipitation data with measurements of winter mass balances or snow water equivalent (Engelhardt and others, 2012; Saloranta, 2012). Results indicate that seNorge both under- and overestimates precipitation depending on location.

Accordingly, we calibrated the seNorge precipitation gradients for the given threshold temperature, to best reproduce the winter mass-balance measurements for the whole glacier area in Norway. The melt factor and the radiation coefficients are calibrated to best reproduce the summer mass-balance measurements. Since melt can also occur during the winter season and snowfall during the summer season, the seasonal parameters are not independent of each other and have to be optimized in an iterative process. The calibration was performed by varying parameter values within physically plausible limits over ranges of predefined steps, aiming to minimize the resulting root-mean-square error (rmse) between modeled and measured seasonal mass balances. The different glacier sizes within this area were accounted for by including a weighting factor representing the surveyed glacier area for each year. The calibration process covers every second year (starting with 1961) of the model period (years of calibration). The remaining years were used to evaluate the calibrated parameter set (years of validation). By this method, we obtained a constant model parameter set which is for both time and space adjusted to the available measurements of the entire model domain.

RESULTS

Calibrated parameter values controlling melt and optimized precipitation gradients are presented in Table 1. In general, measured and modeled mass balances are in good agreement for both winter and summer, yielding an rmse of

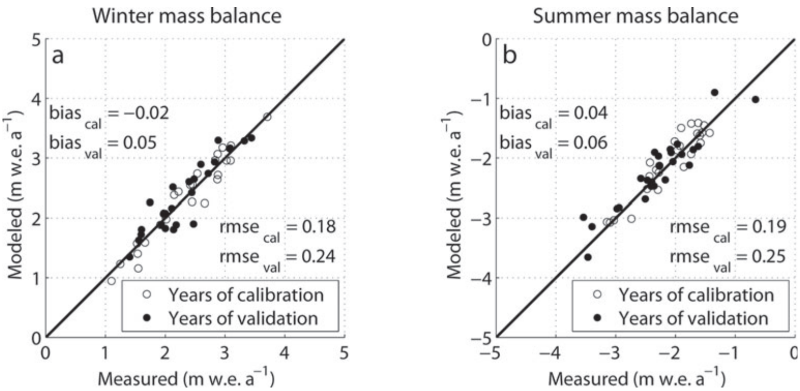

Fig. 4. Specific (a) winter and (b) summer glacier mass balances for each year from 1961 to 2010 for the surveyed glacier area and corresponding model results with an rmse for the years of calibration (odd-numbered years) and validation (even-numbered years).

0.18–0.19 m w.e. a^{-1} for the years of calibration and 0.24–0.25 m w.e. a^{-1} for the years of validation, with a slightly better agreement of winter mass balances (Fig. 4). During the model period, no significant periods of over- or underestimation can be found for the winter balances (Fig. 5a). In contrast, the summer balances were modeled to be less negative for the whole period 1975–85, which corresponds to a period of fewer glacier measurements

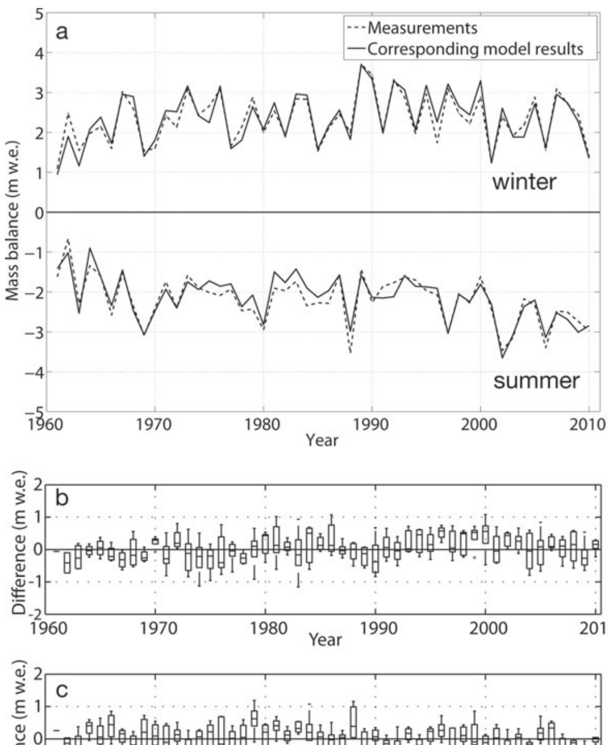

Fig. 5. (a) Modeled and measured seasonal mass balances for the surveyed glacier area of Norway for 1961–2010 and (b, c) annual uncertainties of the seasonal model results based on glacier-wide differences between measurements and model output for (b) winter balances and (c) summer balances.

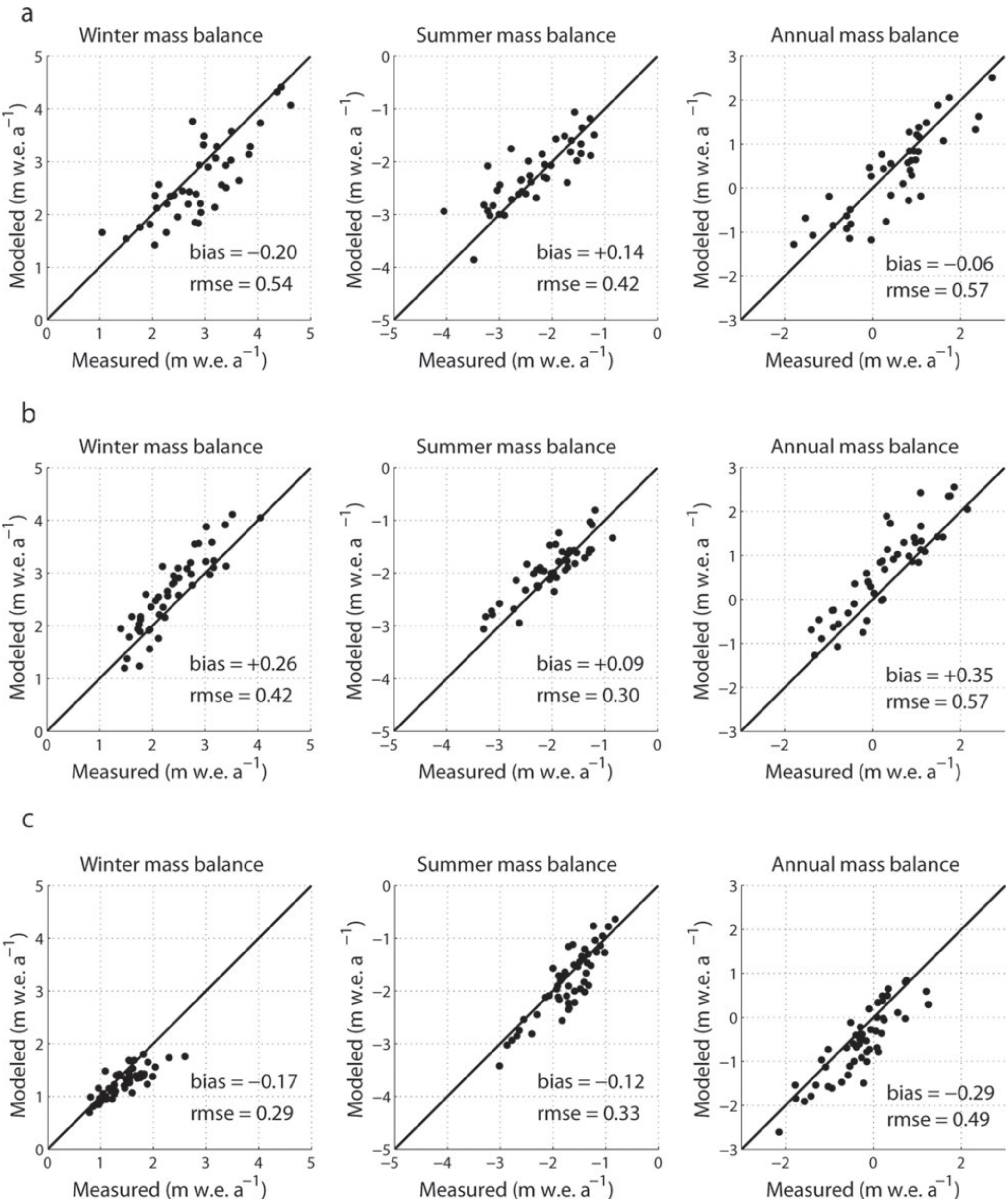

Fig. 6. Modeled versus measured seasonal mass balances from (a) Engabreen, (b) Nigardsbreen and (c) Storbreen using the parameter set of Table 1.

(Fig. 3b) and therefore of lower weight in the calibration process. The uncertainty of glacier-wide balances is on average 0.19 m w.e. a^{-1} for winter and 0.18 m w.e. a^{-1} for summer, but, for individual glaciers, model biases can reach 1 m for winter (Fig. 5b) and summer balances (Fig. 5c). However, no weighting factor representing the change in glacier area covered by measurements is included in this analysis.

Evaluating the parameter set in Table 1 for different locations in Norway, we modeled the seasonal mass balances for three glaciers with an observation period of >40 years: Engabreen, Nigardsbreen and Storbreen. Applying the parameter set to these single glaciers yields larger deviations of the model results compared with the respective measurements, with an rmse of the seasonal balances between 0.29 and 0.54 m w.e. a^{-1} (Fig. 6). Results reveal further that, for Engabreen, modeled winter balances are too negative, while modeled summer balances are too positive (Fig. 6a). For Nigardsbreen both modeled winter and summer balances are too positive (Fig. 6b), whereas both

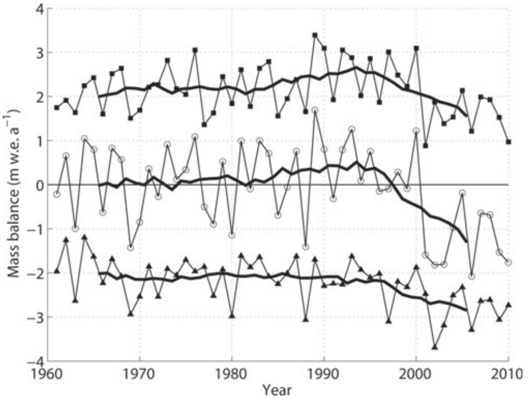

Fig. 7. Modeled winter (squares), summer (triangles) and annual (circles) mass balances for the glacierized area of Norway for 1961–2010 with 10 year central moving average.

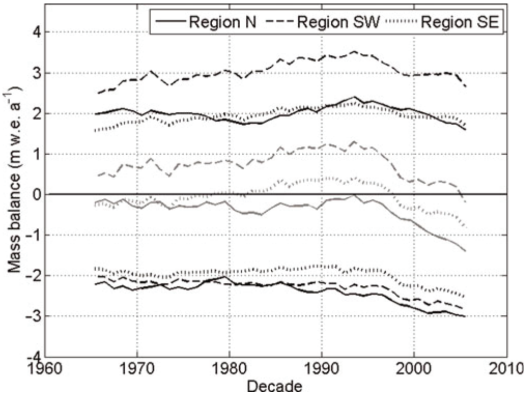

Fig. 8. Ten-year moving average winter (black upper lines), annual (grey center lines) and summer (black lower lines) mass balances for the three regions in Norway defined in Figure 1.

seasonal balances are too negative for Storbreen. Furthermore, results for Storbreen show an increasing bias of the model results for years of large winter balances (Fig. 6c).

Modeled mass balances for the whole glacierized area of Norway show a large year-to-year variability, with values between +1.0 and +3.4 m w.e. a^{-1} for the winter mass balances and between –1.2 and –3.6 m w.e. a^{-1} for the summer mass balances (Fig. 7). Whereas the winter balances show an increasing trend until the 1990s, no obvious trend can be detected for the summer balances for this period. During the first decade of the 21st century, both seasonal balances display noticeably lower values than for the first four decades considered. In the period 1961–2010, the resulting annual mass balances vary between –1.7 and +1.7 m w.e. a^{-1}, with a slightly increasing trend until the 1990s, followed by a drastic decline (Fig. 7). Ten-year averages of winter mass balance show a gradual increase by $\sim$0.5 m w.e. a^{-1} between 1961 and 2000, whereas the summer mass balances appear more constant, with only minor changes of 0.15 m w.e. a^{-1} during this period (Table 2). The slightly more negative summer mass balances in the 1990s were thus overcompensated by increased winter mass balances. The resulting annual mass balances were therefore increasing from values close to zero in the 1960s and 1970s to +0.37 m w.e. a^{-1} in the 1990s. However, in the first decade of the 21st century, the annual mass balances declined to –0.86 m w.e. a^{-1}, with a parameter uncertainty of 0.15 m w.e. a^{-1}. The decline is due to both increased summer ablation and decreased winter accumulation in roughly equal proportions (Table 2). Therefore, the cumulative mass balances reached a maximum at the turn of the century and declined in the period 2000–10, leading to a cumulative mass balance close to zero for the whole modeling period 1961–2010.

Although the parameter set is less valuable at the local scale, we try to retrieve spatial variability of glacier mass balance (Fig. 8) for the three regions of Norway shown in Figure 1a. These regions were defined such that the northern region (N) comprises the geographically more isolated cluster of glaciers. The remaining glacier area, in the south, was further subdivided into two regions, the maritime region along the southwest coast (SW), and the more continental region in the southeast (SE), yielding roughly equal glacier areas for all three regions. In region SW, the winter mass balances are $\sim$1 m higher and show a larger increase between the 1960s and 1990s than in the other two regions where the 10 year moving averages of winter mass balance were more constant. Thus, variations in the average winter mass balance in the country are mostly dependent on variations in region SW. The summer mass balances are most negative in region N and least negative in region SE. However, the regional differences in summer mass balance are much smaller than those for winter mass balance. For all three regions the summer mass balances were almost constant over the last four decades of the 20th century, but about 0.6 m lower in the first decade of the 21st century. The variations of the annual mass balances are thus similar in space and time to those of the winter mass balances and reveal an accelerating mass loss due to both decreasing snow accumulation and intensified melt for the last decade of the modeling period in all three regions. Whereas in region SW the moving average of the annual balances has been positive during almost the whole model period, with values between +0.5 and +1.2 m w.e. a^{-1}, it became negative in the most recent decade. In region N, the annual balances have always been slightly negative during this period, with an increasing negative trend for the last decade. In fact, the strongest thinning for all glaciers in mainland Norway has been observed for Langfjordjøkelen (Andreassen and others, 2012a), a glacier situated in this region.

Table 2. Ten-year average modeled mass balances of the glacierized area of Norway (m w.e. a^{-1})

Decade	Winter mass balance	Summer mass balance	Annual mass balance
1961–70	+1.99	–2.01	–0.02
1971–80	+2.18	–2.13	+0.05
1981–90	+2.38	–2.01	+0.37
1991–2000	+2.54	–2.17	+0.37
2001–10	+1.92	–2.78	–0.86

DISCUSSION

Modeling glacier mass balance on large temporal and spatial scales is a challenge due to the importance of local effects on temperature lapse rate or precipitation gradients, which are underrepresented in the input data. This could lead to a miscalculation of local mass-balance gradients. Some uncertainty is related to the temperature and precipitation input datasets from seNorge, which are available at 1 km horizontal resolution where small glaciers cannot be resolved appropriately. The gridded data depend on the quality of the station measurements, the availability of which varies significantly both in space and time (personal communication from M. Mohr, 2011).

Uncertainties in the mass-balance measurements give rise to imperfect parameter calibrations. Differences between geodetic and direct methods are found at many glaciers both in Norway (Østrem and Haakensen, 1999; Andreassen and others, 2002; Haug and others, 2009) and in other countries (e.g. Krimmel, 1999; Fischer, 2011). These can be due to either incorrect interpolations of point measurements or measurement uncertainties of each of the methods (e.g. Rolstad and others, 2009). For example, Engabreen's cumulative mass-balance record from glaciological measurements is assumed to be overestimated as geodetic measurements indicate a glacier close to balance for the period 1985–2002 (Haug and others, 2009). Preliminary results from recent lidar campaigns confirm this disagreement. At Langfjordjøkelen, the comparison between geodetic and direct methods for the period 1994–2008 reveals better agreement, but the results from the glaciological measurements are still ~0.2 m w.e. a^{-1} less negative than those derived from geodetic methods (Andreassen and others, 2012a). The mass-balance record of Engabreen is currently being homogenized and revised (Andreassen and others, 2012a). Similar work has also started for other glaciers in this study. Revised versions of the direct measurements could lead to a different optimized model parameter set than presented here, and alter the subsequent results.

As the surveyed glaciers account for only 5–10% of all Norwegian glaciers, another source of uncertainty is the use of a single parameter set to model the accumulation and ablation for all glaciers. Although the hypsometry of the surveyed glaciers is representative of the whole glacierized area (Fig. 2), optimized model parameters might be biased to the climate conditions where glacier measurements are performed.

Our model results show the mass-balance distribution for a fixed glacier surface over the model period representing a reference surface mass balance (Elsberg and others, 2001; Cogley and others, 2011). We choose to use a reference surface since changes in glacier mass balance of a reference surface are more directly linked to climate variations than in a traditional mass-balance record. With further glacier retreat, the traditional mass balance could decrease less than the temperature increase would suggest, or even increase in some places as glacierized areas at low altitudes disappear. For our study period, glacier area variations, especially for larger glaciers, are small compared with the model resolution of 1 km. Whereas Langfjordjøkelen, the glacier with the strongest thinning in mainland Norway (Andreassen and others, 2012a), experienced a decrease in area from 5.2 km^2 to 3.6 km^2 between 1966 and 1994 and a further decrease to 3.2 km^2 between 1994 and 2008, Nigardsbreen shows only a minor decrease from 47.8 km^2 to 47.2 km^2 between 1984 and 2009. Moreover, according to a study on Swiss glaciers by Huss and others (2012), about half of the mass balance offset by using reference instead of conventional surface mass balance is compensated by more negative mass balance due to reduced surface heights.

Our adjusted precipitation for elevations below 1350 m a.s.l. is up to 20% lower than in seNorge. This is in agreement with other studies finding seNorge precipitation too high compared with observed snow measurements (Stranden, 2010; Saloranta, 2012). An underestimation of precipitation at higher elevations (>1500 m a.s.l.) has also been found in a previous validation study comparing seNorge precipitation with winter mass-balance measurements at stake positions at various glaciers (Engelhardt and others, 2012). Locally adjusted precipitation gradients would certainly show significant spatial and temporal heterogeneity. The study of Machguth and others (2008) found that modeled glacier mass balance is most sensitive to uncertainties in precipitation data. Therefore, the constant correction of the precipitation gradients might not be appropriate in some regions. However, the aim of the gradient adjustment in our case was to find an average precipitation correction suitable for all glacierized areas of the country and for the whole model period.

We used a spatially uniform and temporally constant parameter set of melt and precipitation factors to reproduce seasonal mass balances for Norway. Using parameters calibrated for each year individually would certainly improve the model results as melt depends on the full energy balance and the single relation of temperature and melt rate varies over time (Huss and others, 2009). Since, in our case, data availability differs strongly from year to year, such an approach would reflect not only the temporal but also the spatial variability of the parameters. In order to take the different data availability into consideration, we use an annual weighting factor depending on the area of observations of each year. With the derived parameter set we can reproduce the seasonal mass balances to within 0.25 m w.e. a^{-1} for the years of validation, which corresponds to a relative uncertainty of 10% of the seasonal balances. However, for individual glaciers the bias of annual mass balances can be quite high (+0.35 m w.e. a^{-1} for Nigardsbreen; Fig. 6b) or, as in the case of Storbreen, show an increasing trend for larger winter balances. For small glaciers in particular, local conditions cannot be resolved and the results should be treated as a general picture for the glacierized area of Norway.

The modeled increase of winter mass balance between 1960 and 2000 reflects the measured increase in winter precipitation in Norway (Hanssen-Bauer and Nordli, 1998). This increase was most pronounced in western Norway, which led to a readvance of various maritime glaciers (Andreassen and others, 2005). A similar readvance of glaciers was observed in New Zealand between 1980 and 2000 (Chinn and others, 2005). However, this was in contrast to the global trend showing negative mass balance and associated glacier retreat for most glaciers over this period (Haeberli and Beniston, 1998; Oerlemans, 2005).

CONCLUSION

Driven by seNorge data, our calibrated model provides for the first time homogeneous and complete time series of seasonal glacier mass balances at high spatial and temporal resolution for all of mainland Norway. This approach is useful to give an overview of both temporal and spatial variability of glacier mass balance since glacier monitoring covers only a small part of the glacierized area and has irregular temporal coverage. The results may be used to assess spatial patterns of mass balance in the present and past and may also contribute to hydrological applications. For smaller regions, locally adjusted parameter sets may be more appropriate. Modeled specific seasonal and annual glacier mass balances for Norway from 1961 to 2010 reveal that although year-to-year variability is high, there were positive trends of winter and net balance between 1961 and 2000. Since 2000 a remarkable decrease in both summer and winter mass balance has occurred. The resulting net mass balance of close to –1 m w.e. a^{-1} for the first decade of the 21st century might only be a glimpse of what can be expected for the future.

ACKNOWLEDGEMENTS

This publication is contribution No. 8 of the Nordic Center of Excellence SVALI, 'Stability and Variations of Arctic Land Ice', funded by the Nordic Top-level Research Initiative (TRI). We thank the glacier group of NVE for providing stake data, Matthias Mohr of the Norwegian Meteorological Institute for providing further information about seNorge, and all staff of NVE and Statkraft who contributed in collecting and providing data for this study. We also thank Scientific Editor Matthias Huss and Daniel Farinotti and Bernhard Hynek for careful reviews, which significantly improved the paper. Helpful comments by Gwenn Flowers are also gratefully acknowledged.

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8.3 Article III

– **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2014): Contribution of snow and glacier melt to the discharge for highly glacierised catchments in Norway. – *Hydrology and Earth System Sciences* **18**, accepted and in press.

Manuscript prepared for Hydrol. Earth Syst. Sci.
with version 5.0 of the LaTeX class copernicus.cls.
Date: 9 January 2014

Contribution of snow and glacier melt to discharge for highly glacierised catchments in Norway

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Abstract. Glacierised catchments show a discharge regime that is strongly influenced by snow and glacier meltwaters. In this study, we modelled the mass balance and discharge rates for three highly glacierised catchments (>50 % glacier cover) in western Norway over the period 1961-2012. The spatial pattern of the catchments follows a gradient in climate continentality from west to east. The model input were gridded temperature and precipitation values from *seNorge* (http://senorge.no) which are available at daily resolution. The model accounted for accumulation of snow, transformation of snow to firn and ice, evaporation and melt. Calibration and validation was performed for each catchment based on measurements of seasonal glacier mass-balances and daily discharge rates. As additional validation data served daily melt rates from sonic rangers located in the ablation zones of two of the glaciers. The discharge sources snowmelt, glacier melt and rain were analysed with respect to spatial variations and temporal evolution.

Model simulations reveal an increase of the relative contribution from glacier melt to total discharge for the three catchments from less than 10 % in the early 1990s to 15-30 % in the late 2000s. The decline in precipitation by 10-20 % in the same period was therefore overcompensated resulting in an increase of annual discharge by 5-20 %. Annual discharge sums and annual glacier melt are strongest correlated with annual and winter precipitation at the most maritime glacier and, with increased climate continentality, variations in both glacier melt contribution and annual discharge are becoming stronger correlated with variations in summer temperatures. Therefore, especially glaciers in more continental climates are vulnerable for decrease in both annual and summer discharge with continued rise of summer temperatures and subsequent decrease in glacier extent. This may lead to significant changes to the discharge regime with increase during spring but decline later in the year especially for catchments in less maritime climate conditions.

1 Introduction

In highly glacierised catchments, meltwater constitutes a larger contribution to annual discharge than rain (Jost et al., 2012). Summer streamflow can be amplified or balanced by the presence of glaciers within the catchment (Dahlke et al., 2012), depending on the degree of glacier coverage and the interannual precipitation distribution. One sixth of the world's population is dependent on water originating from snow or glacier melt (Hock et al., 2006). In Norway, 98 % of the electricity is generated by hydropower (Gebremedhin and De Oliveira Granheim, 2012) and catchments regulated for hydropower include 60 % of the total glacier area (Andreassen et al., 2012). Thus, assessment of meltwater runoff is crucial for both water supply and hydropower applications. Changes in discharge are connected to variations in either air temperature or precipitation or a combination of both. Although future climatic and hydrological projections are subject to large uncertainties, ongoing climate change will result in major changes in both, timing and magnitude of the runoff regime. Glacier retreat and the release of freshwater is expected to be a key element in projections of discharge from glacierised catchments over the next decades (e.g. Huss et al., 2010; Finger et al., 2012). The future contribution of glaciers to discharge in a changing climate is therefore subject to research in many regions of the world (e.g. Farinotti et al., 2012; Immerzeel et al., 2012; Schaner et al., 2012). Using climate model data as forcing, different studies indicate an increase of discharge in spring due to earlier onset of snowmelt, but a decline later in the year due to reduced glacier extent (e.g. STAHL et al., 2008; HUSS et al., 2008). Glacial meltwater can also have relevant impacts to the hydrological regime of larger watersheds further downstream. The study of HUSS (2011) revealed, that for catchments with a size of 100 000 km^2 and 1 % glacier cover in August the contribution of glaciers to discharge can be as high as 25 %.

Modelling melt from glaciers requires a melt model. Those models exist in a large range of different complexities (HOCK et al., 2005). Since meteorological data needed for energy balance models are sparse for mountainous regions, temperature-index models have widely been used (e.g. KONZ and SEIBERT, 2010; JOST et al., 2012; ENGELHARDT et al., 2013) which in the simplest form only employ air temperature and precipitation as meteorological input for snow accumulation and computing melt (see HOCK, 2003, for a review). The use of a temperature-index model has been justified since surface air temperature is the most influential parameter for determining melt. Furthermore, the heat sources shortwave radiation and sensible heat flux, which are especially important for glaciers at high latitudes (SICART et al., 2008), are closely correlated with air temperature (OHMURA, 2001).

Uncertainties in quantifying precipitation in high altitudes due to the lack of measurements represent one of the biggest problems for modelling discharge (VERBUNT et al., 2003). Satellite-derived precipitation datasets can be used as a data source for modelling discharge at larger scales in regions without ground-based measurement (LI et al., 2013). Hydrological models for glacierised catchments have often been applied as grid-based models (e.g. HOCK and NOETZLI, 1997; KLOK et al., 2001). Model performance for discharge modelling improves significantly when seasonal mass balances are used as additional calibration criteria (e.g. FINGER et al., 2011; MAYR et al., 2013)

This study aims to model the contributions to discharge for three highly glacierised catchments in southern Norway along a west-east profile. For calibration we used daily discharge data and seasonal mass balance data based on interpolated point measurements (KJØLLMOEN et al., 2011). The calculations were performed on a daily resolution for the period 1957-2012, including a four-year spin-up period. The model structure is following an approach suggested by HOCK (2005): (1) modelling seasonal glacier mass balances and daily runoff, and (2) discharge routing of rain and meltwater taking into account the different hydraulic properties of snow, firn and ice with respect to their flow rate velocities. For parameter calibration, 10 000 Monte Carlo runs were performed. We used two objective functions, the coefficient of variation for seasonal mass balances (until 2000) and the Nash-Sutcliffe coefficient for daily discharge (until 2010 for two of the catchments and 2011 for the third catchment). The parameter sets for melt and snow accumulation were validated for all catchments using seasonal mass balances for 2001-2012 and daily discharge for 2011-2012 for two of the catchments and 2012 for the third catchment. An additional validation was performed using point measurements in the ablation zones of two of the glaciers. The discharge was divided into the water sources snowmelt, glacier melt and rain. We evaluated differences in the runoff regimes between the three catchments as well as changes over time. Furthermore, we investigated correlations between discharge and the meteorological input.

2 Study sites and input data

The study was carried out for three catchments in southern Norway containing the glaciers Ålfotbreen, Nigardsbreen and Storbreen (Fig. 1) where both seasonal mass balance and discharge measurements are available. The glacier coverage in each catchment is >50 % (Tab. 1) and at each glacier, seasonal mass balance measurements have been carried out for more than 50 yr (ANDREASSEN et al., 2005) following the traditional stratigraphic method (ØSTREM and BRUGMAN, 1991). The catchments of Ålfotbreen and Storbreen are similar in size covering about 8 km^2, whereas the catchment of Nigardsbreen is about eight times as large. At all sites, discharge data are available at daily resolution, with the longest series available for Nigardsbreen (50 yr) and the shortest at Storbreen where measurements started in September 2010.

The catchments are located in similar latitude and reflect therefore an west-east profile from Ålfotbreen close to the Norwegian west coast to Storbreen, which is located east of the main mountain divide. The climate can be characterised as very maritime at Ålfotbreen to moderate continental at Storbreen. The variations in mean annual air temperature during the model period (1961-2012) are smallest for Ålfotbreen and largest for Storbreen (Fig. 2a). The summer temperatures (here: May-September) show a similar progression for all catchments (Fig. 2c) with increasing values from 1961-1970 and from 1995-2005 and constant to slightly decreasing values from 1970-1995 and from 2005-2012. The difference in summer temperature between the sites is mainly reflecting the mean catchment elevation which increases from west (Ålfotbreen) towards east (Storbreen). From the early 1990s to the 2000s all three sites experienced an increase in mean summer temperature by about 1-1.5 K.

Precipitation decreases considerably from west to east. The mean annual precipitation sum ranges from more than 5000 mm for Ålfotbreen to less than 2000 mm for Storbreen (Fig. 2b). In contrast to temperature, the annual precipitation sums show least variations at Storbreen where they remained almost constant between the 1960s and 1990s. Afterwards annual precipitation decreased slightly by about 10 % in the 2000s. Both Ålfotbreen and Nigardsbreen show similar variations in precipitation, however they are more pronounced at Ålfotbreen: An increase in annual precipitation of 50 % (20 %) from the 1960s to the end of the 1980s at Ålfotbreen (Nigardsbreen) is followed by a decline of 20 % (10 %) to-

wards the end of the 2000s (Fig. 2b). Winter precipitation (here: October-April), which predominantly falls as snow, follows for all catchments a similar pattern compared to the annual precipitation. On average, winter precipitation yields about two thirds of the annual sums (Fig. 2d).
For the study we used the gridded temperature and precipitation from *seNorge* (www.senorge.no). The data are based on station measurements which are interpolated on a 1 km horizontal grid for all of mainland Norway on a daily basis from 1957 to present Mohr (2008). Despite some weaknesses with the inter- and extrapolation of precipitation in mountainous regions, different evaluation studies (Mohr, 2009; Dyrrdal, 2010; Engelhardt et al., 2012; Saloranta, 2012) found the gridded data of *seNorge* to be suitable for mass-balance modelling especially due to its high spatial resolution.

3 Methods

3.1 Precipitation correction

To account for uncertainties in the precipitation data from *seNorge* associated especially with the vertical adjustment, we applied a constant precipitation correction factor for each catchment to fulfil the (accumulated) water balance over the hydrological years (1 October - 30 September) of available discharge data.
Neglecting in- or outflow of groundwater, the water balance equation reads (all terms in m a^{-1}):

$$P = Q + V + \Delta S \tag{1}$$

where P denotes precipitation, Q discharge and V evaporation. ΔS is a storage term accounting for all water that remains in or additionally leaves the domain.
Snow- or glacier melt within the domain is therefore a negative contribution to the storage term. Considering highly glacierised catchments, we assumed the storage term to be the accumulated glacier mass balance over the period of measurements. Outside the glacierised areas, no storage was assumed. For evaporation we used the gridded data provided from *seNorge* which were only calculated for the non-glacierised areas and set to zero for the glacierised areas (Sælthun, 1996). This is justified since evaporation and condensation on glaciers may balance each other and their net effect is not likely to influence discharge in significant way (e.g. Braun et al., 1994). Since the gridded precipitation data from *seNorge* for the glacier parts of all catchments (P_{g}) have already been evaluated in the study by Engelhardt et al. (2012), we now used the calculated precipitation correction factors (F_{g}) from that study for the glacierised areas and calculated the correction factors for the precipitation (P_{ng}) of the non-glacierised parts (F_{ng}) of the catchments. The water balance equation for the glacierised and non-glacierised areas was then modified to

$$Q \quad = \quad \underbrace{\frac{P_g}{F_{\mathrm{g}}} - \Delta S}_{\text{glacier area}} \quad + \quad \underbrace{\frac{P_{\mathrm{ng}}}{F_{\mathrm{ng}}} - V}_{\text{non-glacier area}} \quad . \tag{2}$$

Using the measurements of accumulated mass balance (e.g. Kjøllmoen et al., 2011) and discharge, the water balance was calculated over the period of available discharge data which is 50 (hydrological) years for Nigardsbreen, 18 years for Ålfotbreen and two years for Storbreen. The correction factors F_{ng} of the *seNorge* precipitation were calculated as an average over the respective periods (Tab. 2).
With the gained correction factors, the precipitation input for the model (P_{input}) is dependent on the grid point location (representing glacierised or non-glacierised area) and was calculated to

$$P_{\mathrm{input}} = \frac{P_{\mathrm{seNorge}}}{F_{\mathrm{g/ng}}}. \tag{3}$$

3.2 Model set-up

The study was performed with a conceptual model based on a temperature index approach including potential solar radiation. The glacier mass balances and meltwater runoff were calculated using air temperature and the corrected precipitation from *seNorge* (section 3.1) as input. The model runs independently for each grid cell on a daily resolution. Despite of the 1 km grid resolution, the model accounts for smaller areas along the glacier and catchment margins by weighting each grid cell with its contribution to the catchment and glacier ratio. The calculations covered the hydrological years 1961-2012 (1 October 1960 - 30 September 2012) and a preceding spin-up period (1957-1960) to accumulate snow and firn. The model accounts for mass gain due to accumulation of snow and mass loss due to evaporation and melting of snow and ice. The transition from snow to rain occurs within an interval of 2 K where the precipitation linearly shifts from snow to rain. The centre of this interval is denoted as the threshold temperature for snow (T_s).
To account for the transition of snow to firn and ice, snow that has not melted away during summer was defined to become firn at the beginning of each hydrological year (1 October). Additionally, 25 % of the existing firn was assumed to become ice, leading to an average transition time from firn to ice of 4 years which is in accordance to a simple time function introduced by Martinec (1977). The conceptual model calculates daily melt of snow, firn or ice $M_{\mathrm{snow/ice}}$ by using a distributed temperature-index approach including potential solar radiation as used e.g. in Hock (1999) or Engelhardt et al. (2013). Melt is calculated if the *seNorge* temperature $T_{\mathrm{sn}} > T_{\mathrm{m}}$ (threshold temperature for melt):

$$M_{\mathrm{snow/firn/ice}} = (\Theta + R_{\mathrm{snow/firn/ice}} \cdot I) \cdot (T_{\mathrm{sn}} - T_{\mathrm{m}}), \tag{4}$$

with the melt factor Θ, the respective radiation coefficients for snow, firn and ice $R_{\mathrm{snow/firn/ice}}$ and the potential direct solar radiation *I*. The potential solar radiation is dependent on latitude and day of year, and its usage effectuates a sinusoidal variation of the melt factor in the course of a year. Modifications due to exposition or shading effects of surrounding slopes were not accounted for as the model grid resolution would not appropriately resolve these phenomena. However, using potential radiation can significantly increase model performance (HUSS et al., 2009). Since the melt efficiency of firn is higher than for snow but lower than for ice, the radiation factors for firn (R_{firn}) were assumed to be the mean of the ones for snow (R_{snow}) and ice (R_{ice}). At each grid point, firn started to melt when the snow has melted and ice starts to melt, once the firn has melted away.

The model calculates the reference surface mass balance (ELSBERG et al., 2001). The area on which the calculations are based on, is the same area for which the available glacier mass balance measurements have been performed (e.g. KJØLLMOEN et al., 2011). This glacier area was e.g. for Nigardsbreen 47.8 km^2 from 1984-2008 and was updated to 47.2 km^2 in 2009. All changes in glacier area during the model period are not larger than 6 % of the respective glacier area. To account even for such small area changes in the model, the glacier melt contribution of the grid point representing the lowest glacier altitude is changed by adjusting the glacier ratio of this grid point.

Besides melting, the model also accounts for a delay in runoff by using a linear reservoir for daily discharge for each catchment. The water from melt and rain is distributed over time using three storage constants for the linear reservoirs depending on the surface property snow, firn or ice.

At a daily time step (t) the reservoirs (W) for each grid point (i) were updated based on the previous values $W_i(t-1)$ and the calculated meltwater and rain for this location:

$$W_i(t) \;=\; W_i(t-1) + M_i(t) + R_i(t), \tag{5}$$

where M denotes the calculated melt rates and R the rain (precipitation at T > T_s).

The discharge for each grid q_i was calculated individually using a storage constant ($c_{\text{snow/firn/ice}}$) dependent on the surface property of this grid point:

$$q_i(t) \;=\; c_{\text{snow/firn/ice}} \cdot W_i(t). \tag{6}$$

The daily model resolution allowed the usage of a constant rather than a time-varying storage coefficient as used e.g. in STAHL et al. (2008). No water storage was applied for grid cells which are not covered by snow, firn or ice since a fast runoff is assumed for these areas located in mountainous terrain and close to the discharge station. Thus, rain was treated like meltwater when falling on snow, firn, or ice, but was counted as discharge for the same day falling on areas free of snow or ice.

After the daily discharge rate was calculated, the water reservoir was updated and the daily simulated discharge for the whole catchment (Q_m) was calculated as the sum from all grid points:

$$W_i(t) \;=\; W_i(t) - q_i(t) \tag{7}$$

$$Q_m(t) \;=\; \sum_i q_i(t) \tag{8}$$

3.3 Calibration of model parameters and validation of model performance

For the calibration scheme we used for each catchment a Monte Carlo run of 10 000 random parameter sets consisting of eight parameters given in Tab. 3. For each parameter set, two optimization criteria were calculated: (1) the coefficient of variation (c_v) between measured (meas) and modelled (mod) glacier-wide seasonal mass balances (b) for the period 1961-2000, and (2) the Nash-Sutcliffe coefficient (E) for daily discharge for the period 1995-2010 at Ålfotbreen, 1963-2010 at Nigardsbreen, and for the year 2011 at Storbreen:

$$c_v \;=\; \frac{\sigma}{\overline{|\mathrm{b}_{\text{meas}}|}} \quad \text{with} \tag{9}$$

$$\sigma \;=\; \sqrt{\frac{\overline{(\mathrm{b}_{\text{mod}} - \mathrm{b}_{\text{meas}})^2}}{n}} \quad \text{and} \tag{10}$$

$$E \;=\; 1 \;-\; \frac{\sum (Q_0 - Q_m)^2}{\sum \left(Q_0 - \overline{Q_0}\right)^2}, \tag{11}$$

where n denotes the number of measured b and Q_0 measured daily discharge sums.

Following an approach by KONZ and SEIBERT (2010), the combination of the two optimization criteria was performed by ranking the parameter sets separately according to their mass balance and runoff qualities. The ranks were summed and the 100 parameter sets with the lowest rank sums were selected. The ensemble average of the selected parameter values is given in Tab. 3.

For each catchment, the model was run for each of the best 100 parameter sets over the period of available *seNorge* data (1957-2012). The model runs were validated for all catchments with the seasonal mass balances for 2001-2012 and with daily discharge for 2011-2012 for Ålfotbreen and Nigardsbreen and 2012 for Storbreen.

As additional validation of the model performance, we used weekly melt rates measured with sonic rangers in the ablations zones of Storbreen (ANDREASSEN et al., 2008) and Nigardsbreen. Data were available for 84 weeks with melt during the period 2002-2012 for Storbreen and for 43 weeks from the melt seasons 2011 and 2012 for Nigardsbreen. Weeks with data gaps or snow fall events were excluded. The melt rates at these two point locations were calculated by using the ensemble mean of the calibrated parameter set. The temperature and precipitation input for the sonic ranger locations were retrieved by interpolating the daily *seNorge* temperature and precipitation data to the horizontal sonic ranger positions and adjusting the data to the altitude, using the vertical gradients from the *seNorge* routines.

4 Results

The model performance for seasonal mass balance and daily discharge expressed by coefficient of variation and Nash-Sutcliffe coefficient was increasing from Ålfotbreen, the most maritime study site towards Storbreen (Tab. 3). Whereas there was little difference in modelling seasonal mass balances with coefficient of variation values between 0.15 and 0.20, daily discharge was modelled better for both Nigardsbreen and Storbreen with a Nash-Sutcliffe coefficient E between 0.85 and 0.91 than at Ålfotbreen (E = 0.76-0.78).
The parameter uncertainty of the different individual model parameters in the best 100 model runs is given in Fig. 3. There was little difference in the uncertainty of the melt threshold temperature between the catchments. The snow threshold temperature showed largest uncertainty at Ålfotbreen, where this parameter showed with 2.5 °C the largest median value. For the melt parameters, the uncertainty in the two radiation coefficients was larger than for the melt factor. The storage coefficients were increasing from snow to ice, yielding faster runoff for meltwater from ice melt than from snowmelt.
The seasonal mass balances for the validation period 2001-2012 were better modelled for the glaciers Nigardsbreen and Storbreen where absolute values of mass balances were smaller and year-to-year variations lower than at Ålfotbreen (Fig. 4).
The validation of the model parameter for calculating weekly melt at the sonic ranger positions showed a larger spread at Storbreen than at Nigardsbreen (Fig. 5). However for Nigardsbreen the model had a tendency to underestimate high discharge values. At both locations the bias between modelled and measured melt rates was low, which means that the accumulated melt was modelled close to the measurements.
Daily discharge was simulated well at all catchments (Fig. 6). Although daily peak flows can be as high as 70 mm d^{-1} at all catchments, variations in daily discharge was largest at Ålfotbreen and smallest at Nigardsbreen. Nigardsbreen and Storbreen showed a similar discharge pattern in the course of the year.
The annual sums of the modelled specific discharge over the period 1961-2012 revealed an overall increase for all three evaluated catchments for this period by about 20 % (Fig. 7), but also periods of declining discharge. At Ålfotbreen the discharge increased by about 40 % between the 1960s and the late 1980s followed by a large variability within the following two decades with annual discharge sums ranging from 4-8 m a^{-1}. At Nigardsbreen and Storbreen, the annual discharge showed much smaller changes within the model period. Nevertheless, the 2000s were the decade when discharge was highest for these two catchments and about 20 % above average. The measured annual discharge sums corresponded quite well with the model simulations. However the available data series for Storbreen were quite short with only 2 years of measurements.
Larger variations than for the discharge sums were visible in the proportion of the contributing discharge sources (Fig. 8). For all catchments the largest contribution denoted from snowmelt which accounted roughly for 60 % of the annual discharge. Until the 1990s, Storbreen showed the highest relative contribution from snowmelt among the study sites with values up to 70 % in the 5-year moving averages in the 1960s and early 1990s. Most remarkable was the decrease from the 1990s to the 2000s, when the snowmelt contribution to discharge decreased at all sites from 65-70 % to 50-60 %. This decrease was larger for the small glaciers Ålfotbreen and Storbreen, whereas at Nigardsbreen the contribution of snowmelt to discharge during the model period was most constant of all catchments. Among our study sites, the relative contribution from glacier melt became larger with increasing climate continentality from west (Ålfotbreen) to east (Storbreen). A decrease from the 1970s to a minimum in the early 1990s, when at all sites less than 10 % of the annual discharge was originating in glacier melt, was followed by an increase in the 2000s, surpassing the high values from the 1960s and 1970s. At Storbreen the relative contribution from glacier melt accounted for more than 25 % of the annual discharge in the first decade of the 21$^{\text{st}}$ century.
The remaining water source for discharge is rain. Its relative contribution was highest for Ålfotbreen (∼37 %), moderate for Nigardsbreen (∼27 %) and lowest for Storbreen (∼19 %). Whereas changes over time were smallest at Storbreen, for Ålfotbreen and to a lesser extend also for Nigardsbreen the relative component of rain to discharge had a maximum in the 1980s and a minimum in the 1960s and 1990s.
The uncertainty of the contributing discharge sources among the 100 best ranked parameter sets was highest for snowmelt, spreading in a band of 5 %, and lowest for glacier melt. For all discharge sources, the uncertainty was slightly higher for Ålfotbreen than for the other catchments.
The evaluation of the monthly discharge for the periods 1991-2000 and 2001-2010 revealed that for all three catchments the majority in discharge occured in the three months June, July and August (Fig. 9/10) accounting for about 60 % of the annual discharge for Ålfotbreen, 75 % for Nigardsbreen and 85 % for Storbreen. At all sites, the maximum of both, snowmelt and total discharge is in July. However from the 1990s to the 2000s snowmelt increased in May and June and decreased from July to September. Whereas in the 2000s, in June for all three catchments about 80 % of the discharge derived from snowmelt, this proportion decreased within two months in August to less than half of the discharge for Nigardsbreen and to a third for Ålfotbreen and Storbreen. The maximum of glacier melt occurred at all catchments in August. In the 2000s glacier melt accounted for about a third of the discharge in August at Ålfotbreen and Nigardsbreen, and

more than 50 % at Storbreen.

The most obvious difference between the two decades 1991-2000 and 2000-2010 is the increase in glacier melt at all sites. Due to increased snowmelt in May and June and increased glacier melt in August and September, the total discharge increased in almost all months from May throughout October. Correlation between meteorological input and annual discharge revealed a very high correlation of annual discharge with annual precipitation at Ålfotbreen (Tab. 4). The correlation was almost as high with winter precipitation (October-April). However, at Nigardsbreen and Storbreen, annual discharge was highest correlated with summer temperatures (May-September). Whereas at Storbreen summer temperatures were also strongest correlated with annual glacier melt (Tab. 5), both Nigardsbreen and Ålfotbreen show that glacier melt was strongly negatively correlated with the annual precipitation sum.

5 Discussion

The modelled increase in annual discharge at Ålfotbreen from the 1960s to 1980s corresponds with an increase in precipitation during this period. Although mean summer temperatures at this site remained unchanged until the 1990s, the relative contribution from glacier melt decreased. The increasing precipitation was leading to both, increased discharge and to a mass gain since more of the winter snow did not melt away. Measurements show an average annual mass balance on Ålfotbreen of +0.5 m a^{-1} from 1965 to 1995 (KJØLLMOEN et al., 2011). The largest variations in annual discharge at Ålfotbreen can be attributed to larger variations in precipitation and to the higher mass-balance sensitivity of maritime glaciers to precipitation changes which was also found in previous studies (e.g. XU et al., 2012). On Nigardsbreen and Storbreen the increase in precipitation from the 1960s to 1990s was much smaller. In addition, the coinciding decrease in glacier melt led to almost unchanged mean discharge for these two catchments until the 1990s. In general, an increase in winter precipitation leads to increased snowfall, positive mass balances and reduced glacier melt during summer. At Nigardsbreen, increased winter precipitation was the reason of positive mass balances and advance of the glacier tongue in the 1990s (WINKLER et al., 2009). While the annual precipitation slightly decreased at Nigardsbreen and Storbreen in the 2000s, the increase in discharge in the same period can be attributed to the increased summer temperature by 1-1.5 K. At all three sites, increasing temperatures after the mid 1990s and decreasing precipitation resulted in reduced snow depths and increased glacier melt.

Among the three study sites, annual discharge at Ålfotbreen is most sensitive to changes in precipitation (Tab. 4). The contribution of snow from areas outside the glacier at Ålfotbreen together with the large contribution from rain are the dominant factors for annual discharge at this site. At Nigardsbreen, where the glacier free area is $<$30 % and where precipitation is much smaller than at Ålfotbreen, the annual discharge is like for Storbreen most sensitive to summer temperature.

The correlation of glacier melt to temperature changes is largest on Storbreen (Tab. 5). Compared to Ålfotbreen, the annual precipitation at Storbreen is only about a third. The snow depth at the end of winter is accordingly lower which leads to an earlier start of bare ice on Storbreen. Variations in glacier melt are therefore stronger correlated to variations in summer temperature at Storbreen, whereas at both, Nigardsbreen and Ålfotbreen glacier melt is closest correlated to precipitation. A slightly higher correlation of glacier melt to annual rather than winter precipitation at these two sites is due to the fact that also summer precipitation indirectly affects glacier melt. Rainy days in summer coincide with more than average cloud cover and lower temperatures. In addition, snowfall events in summer even prevent glacier melt for several days (OERLEMANS, 2004).

Previous studies (e.g. CHEN and OHMURA, 1990) found that with increasing glacierization of a catchment, the occurrence of the maximum monthly runoff is delayed, and with decreasing glacier coverage the correlation of annual discharge with annual precipitation increases. We can partly sustain this finding for the lowest glaciated catchment of Ålfotbreen showing the highest correlation of annual discharge with annual precipitation sum whereas for Nigardsbreen and Storbreen, the annual discharge is highest correlated with mean summer temperature. However, considering the relatively small range of glacier cover difference in our study sites (51-72 %), the correlation of annual discharge with annual precipitation reflects predominantly the climate continentality of the catchments rather then glacier coverage. Long-term forecast for western Norway indicates that a rise in the summer temperature by about 2 °C by the end of the 21^{st} century (NESJE et al., 2008). For Storbreen, such an increase will double the period of potential glacier melt (ANDREASSEN and OERLEMANS, 2009). High glacier melt rates lead to a decrease of the glacier area and thus discharge would decrease especially in August when at Storbreen for 2001-2010 glacier melt accounted on average for more than 50 % of the discharge (Fig. 10c), which is in accordance to similar studies for the Alps (e.g. FINGER et al., 2012).

6 Conclusions

In this study annual discharge series for the past five decades were modelled for three glacierised catchments in Norway. The model was calibrated through comparisons of modelled and observed seasonal mass-balances and daily discharge sums. The time series of modelled annual discharge were split up in their contributing water sources snowmelt and glacier melt and rain. Changes in these contributing sources during the modelling period were much larger than variations in annual discharge sums.

Due to their location in different climate settings, the three studied catchments are representative for glaciers in Norway. Although for discharge, both year-to-year variability and variability throughout the year is largest at Ålfotbreen, the catchments closest to the western coast, glaciers with greater distance to the coast like Storbreen would experience larger changes in the discharge regime. Differences between the catchments in the seasonal discharge regimes and in year-to-year variability could be attributed to the large precipitation gradient and therefore to increasing climate continentality from west to east rather than differences in catchment size or degree of glacier coverage.

Discharge at the most maritime glacier Ålfotbreen is strongest correlated to changes in precipitation whereas discharge at the most continental catchment of Storbreen is strongest correlated to changes in summer temperatures. Especially for Storbreen, glacier melt is a large contributor to discharge in late summer which may lead to reduced discharge in this time of the year when its glacier area decreases. In order to extrapolate the results into the future, a reduction of the glacierised area has to be accounted for when enhanced glacier melt has caused glacier volume to decrease significantly.

Acknowledgements. This publication is contribution number 29 of the Nordic Center of Excellence SVALI, “Stability and Variations of Arctic Land Ice”, funded by the Nordic Top-level Research Initiative (TRI).

The authors want to thank Statkraft and the glacier group of the Norwegian Water Resources and Energy Directorate (NVE) for supporting fieldwork, as well as collecting and providing data for this study. We also thank the Institute for Marine and Atmospheric Research, Utrecht (IMAU) for operating and providing data from the automatic weather station on Storbreen.

The authors want to thank the scientific editor Jan Seibert and especially two anonymous referees who contributed with constructive comments to significantly improve the manuscript.

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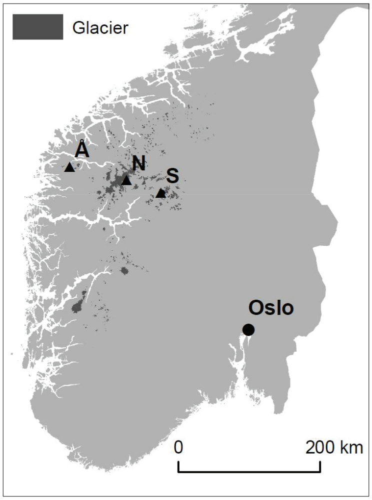


Fig. 1. Location of the study sites Ålfotbreen (Å), Nigardsbreen (N) and Storbreen (S) within the glacierised areas in southern Norway.

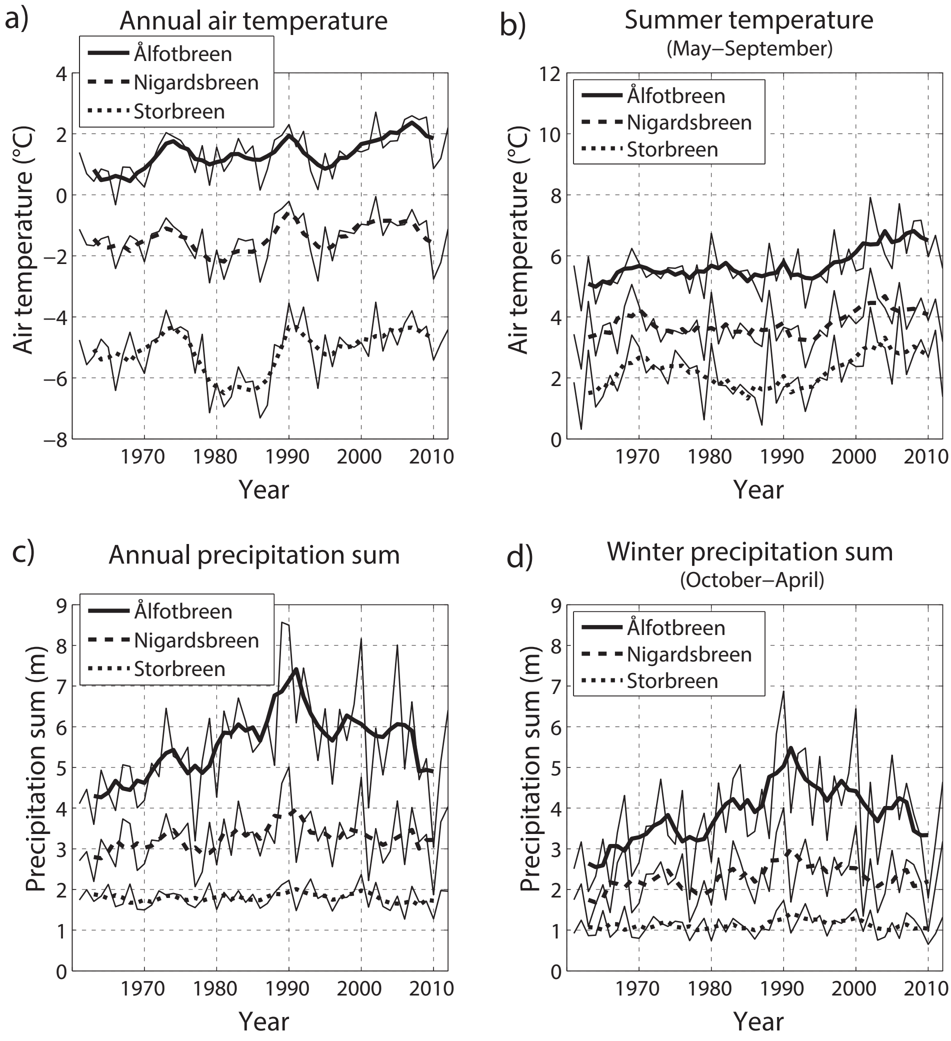


Fig. 2. Air temperature and precipitation data with 5-year moving averages for the three catchments based on *seNorge* data.

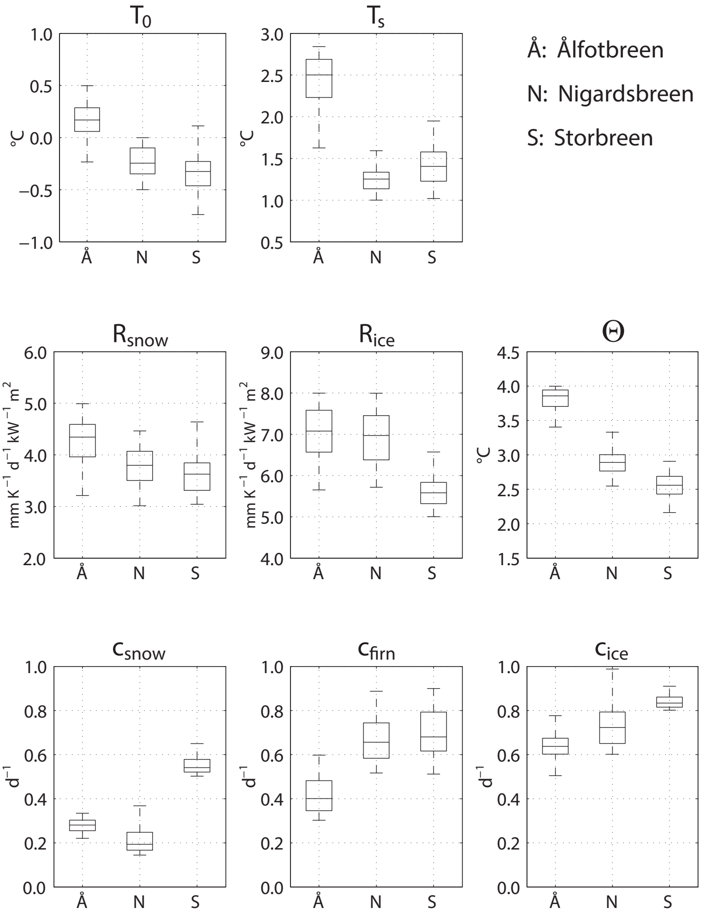


Fig. 3. Parameter uncertainty of the 100 best runs. In each box, the central mark is the median, the edges of the box are the 25^{th} and 75^{th} percentiles, the whiskers extend to the most extreme data points. The ordinate indicate the parameter range in the calibration scheme. Parameter description and median values are given in Tab. 3.

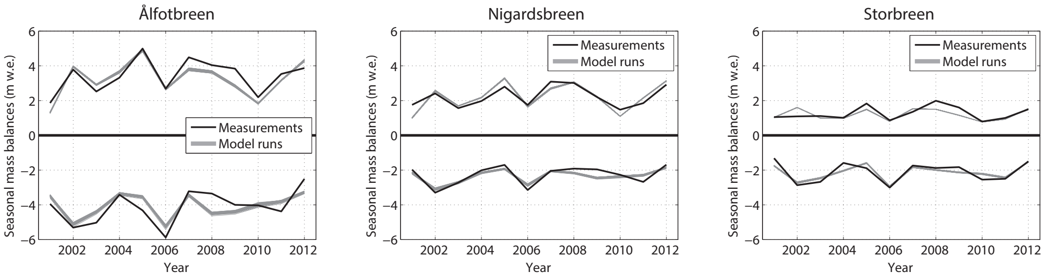


Fig. 4. Model performance for seasonal glacier mass balances for the three catchments for the validation period 2001-2012.

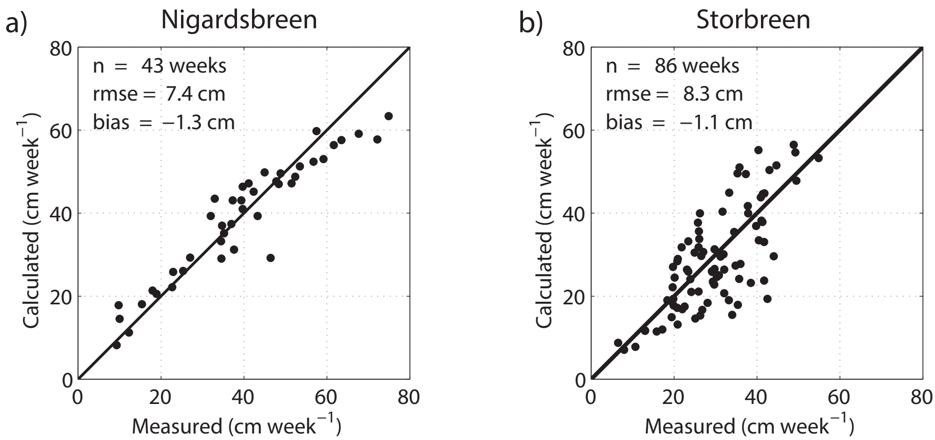


Fig. 5. Model performance for weekly melt at the sonic ranger position of Nigardsbreen (2011-2012) and Storbreen (2002-2012). Data for the modellings represent the mean of the best 100 model runs.

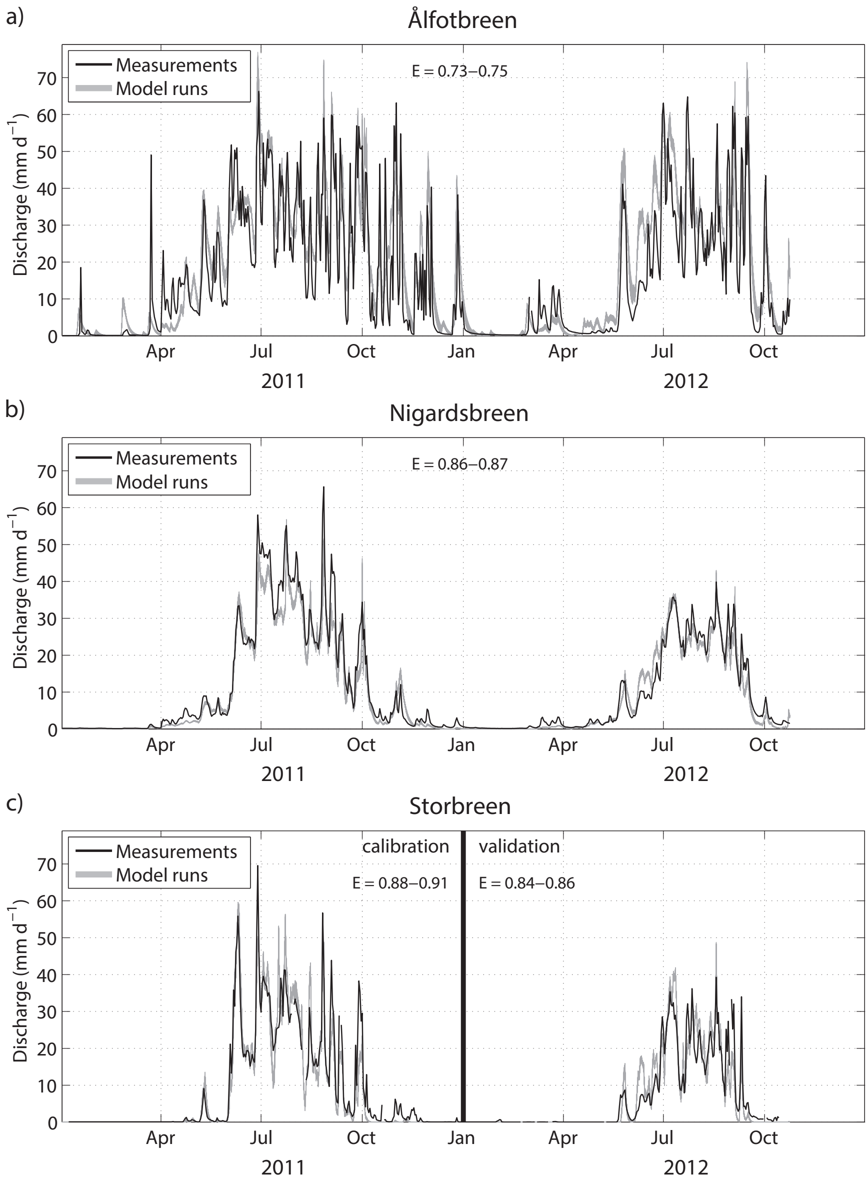


Fig. 6. Model performance for daily discharge sums at the three catchments for the validation years 2011 and 2012. Note: At Storbreen, daily discharge for 2011 is used for calibration, and 2012 for validation.

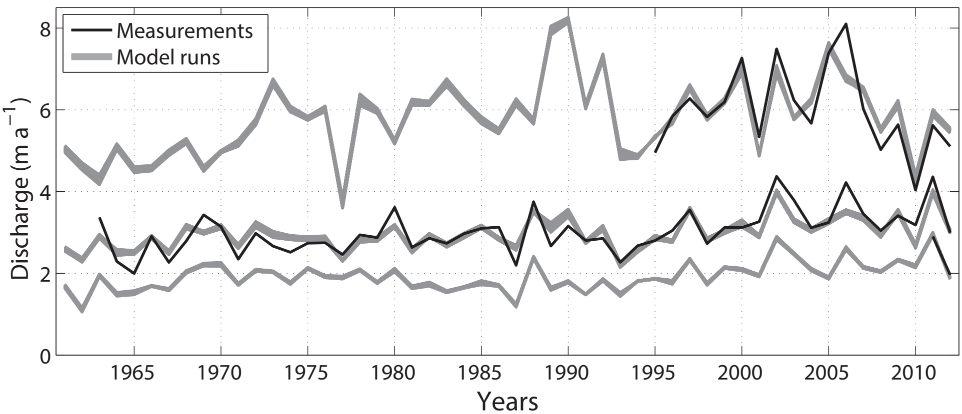


Fig. 7. Mean annual discharge sums for the catchments of Ålfotbreen (upper lines), Nigardsbreen (centre lines) and Storbreen (lower lines) for the period 1961-2012.

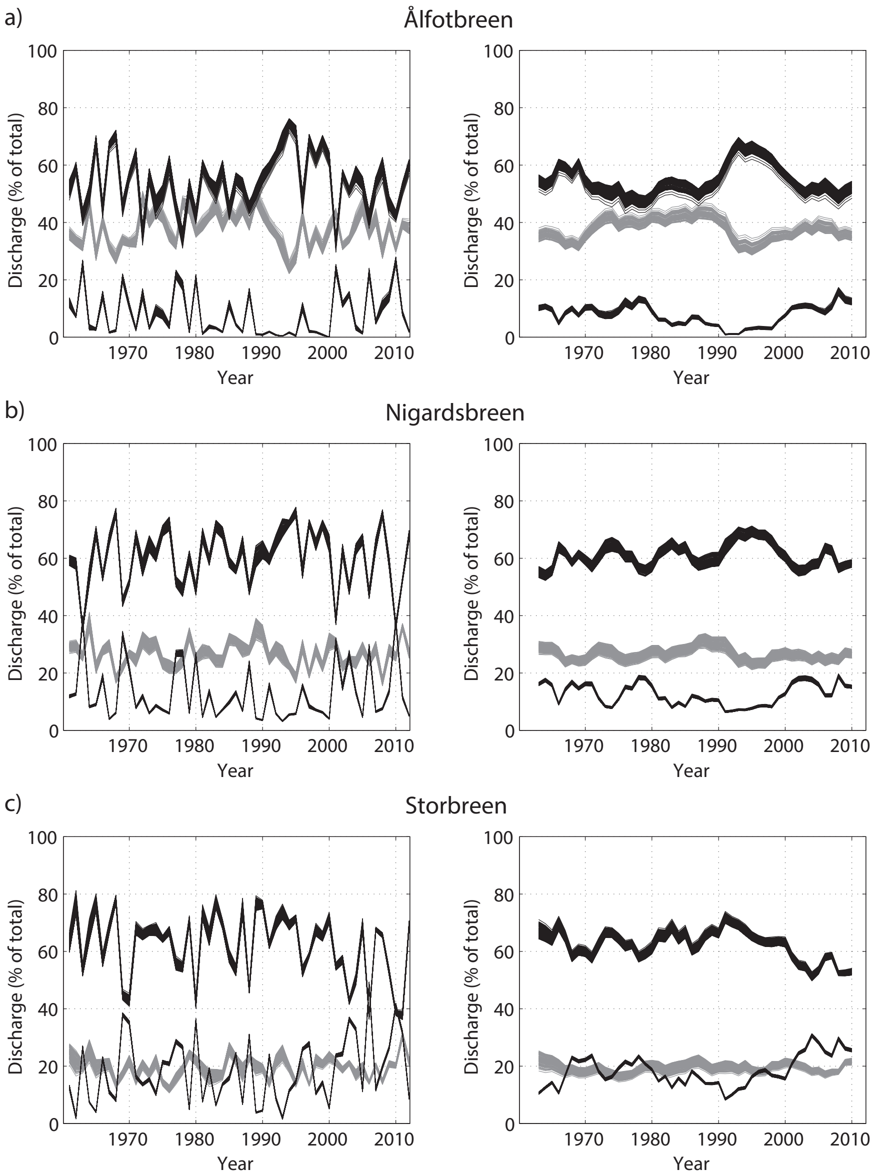


Fig. 8. Relative proportions of the contributing sources to the annual discharge (left column), and the respective 5-year moving average (right column). Snowmelt is represented by the upper black lines, glacier melt by the lower black lines and rain by the grey lines.

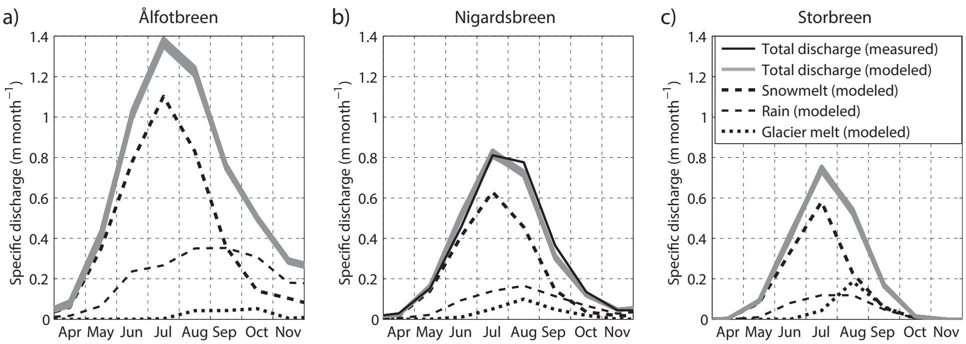


Fig. 9. Modelled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 1991-2000. Data for the contributing sources represent the mean of the best 100 model runs.

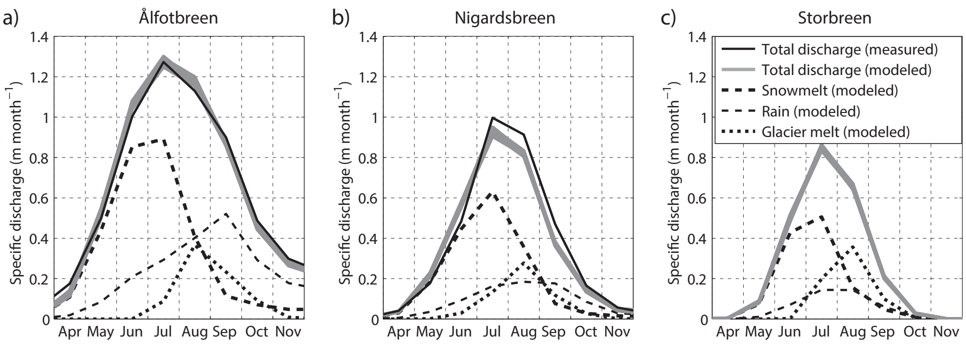


Fig. 10. Modelled monthly discharge rates and their contributing sources for Ålfotbreen, Nigardsbreen and Storbreen averaged for the period 2001-2010. Data for the contributing sources represent the mean of the best 100 model runs.

Table 1. Overview of the three study catchments.

	Ålfotbreen	Nigardsbreen	Storbreen
Catchment size (km^2)	8.3	66	8.0
Glacier coverage (%)	51	72	65
Latitude (°N)	61.8	61.7	61.6
Longitude (°E)	5.6	7.1	8.1
Mean catchment elevation (m a.s.l.)	927	1401	1597
Start of mass balance measurements	1963	1962	1949
Start of discharge measurements	1994	1962	2010

Table 2. Water balance components (in m a^{-1}) and precipitation correction factors (F) for the glacierised (g) and non-glacierised (ng) parts of the three catchments. All water balance components are specific quantities for the respective catchment area (Tab. 1).

	Ålfotbreen	Nigardsbreen	Storbreen
Period (hydrological years)	1995-2012	1963-2012	2011-2012
Precipitation (g)	3.37	2.67	1.06
Precipitation (ng)	2.43	0.62	0.64
Discharge	5.66	3.01	2.60
Evaporation	0.06	0.05	0.02
Accumulated mass balance	-0.24	0.25	-0.65
F_{g} (from *Engelhardt et al., 2012)*	1.01	1.00	0.80
F_{ng}	1.13	0.99	1.00

Table 3. Median of the 100 best parameter sets and model performance (coefficients of variation for seasonal mass balances and Nash-Sutcliffe coefficient for daily discharge sums) of the 100 best ensemble runs for the calibration periods.

Parameter	Description	Ålfotbreen	Nigardsbreen	Storbreen	Unit
T_0	melt threshold factor	0.2	-0.2	-0.3	°C
T_s	snow threshold factor	2.5	1.3	1.4	°C
R_{snow}	radiation coefficient for snow	4.3	3.8	3.6	mm K^{-1} d^{-1} kW^{-1} m^2
R_{ice}	radiation coefficient for ice	7.1	7.0	5.6	mm K^{-1} d^{-1} kW^{-1} m^2
Θ	melt factor	3.9	2.9	2.6	mm K^{-1} d^{-1}
c_{snow}	storage constant for snow	0.28	0.19	0.54	d^{-1}
c_{firn}	storage constant for firn	0.40	0.66	0.68	d^{-1}
c_{ice}	storage constant for ice	0.64	0.72	0.83	d^{-1}
c_v	coefficient of variation	0.18-0.20	0.16-0.17	0.15-0.16	-
E	Nash-Sutcliffe coefficient	0.76-0.78	0.85-0.88	0.88-0.91	-

Table 4. Correlation coefficient of annual discharge sums (October-September) for the model period 2001-2010.

	Ålfotbreen	Nigardsbreen	Storbreen
Mean annual air temperature (October-September)	0.66	0.57	0.48
Mean summer temperature (May-September)	0.21	0.78	0.93
Annual precipitation sum (October-September)	0.87	0.17	0.05
Winter precipitation sum (October-April)	0.85	0.20	0.01

Table 5. Correlation coefficient of annual glacier melt for the model period 2001-2010.

	Ålfotbreen	Nigardsbreen	Storbreen
Mean annual air temperature (October-September)	-0.15	-0.51	-0.06
Mean summer temperature (May-September)	0.32	0.30	0.75
Annual precipitation sum (October-September)	-0.76	-0.88	-0.66
Winter precipitation sum (October-April)	-0.67	-0.85	-0.66

8.4 Article IV

– Li Lu, **Engelhardt M.**, Xu Chong-Yu., Jain S. K., Singh V. P. (2013): Comparison of satellite-based and reanalyzed precipitation as input to glacio-hydrological modeling for Beas river basin, Northern India. – *Cold and Mountain Region Hydrological Systems Under Climate Change: Towards Improved Projections*, Proceedings of H02, IAHS-IAPSO-IASPEI Assembly, July 2013, Gothenburg, Sweden), International Association of Hydrological Sciences (IAHS) Publication number 360, 45-52.

Chapter 9

Appendix

9.1 PhD Courses

- Spring 2010: GEO9440 - *Cryospheric modelling*, University of Oslo, Norway.
- Spring 2010: MNSES9100 - *Science, Ethics and Society*, University of Oslo, Norway.
- Spring 2010: Geosciences - Special Syllabus organized by University of Alaska Fairbanks, *International Summer School in Glaciology*, 07-19 June 2010, McCarthy, Alaska, USA.
- Fall 2010: GEO9441 - *Field course in glacial and periglacial geomorphology/geocryology*, University of Oslo, Norway.
- Fall 2010: Geosciences - Special Syllabus organized by Utrecht University, *Karthaus Summer School on Ice Sheets and Glaciers in the Climate System*, 14-24 September 2010, Karthaus, South Tyrol.
- Spring 2011: Geosciences - Special Syllabus organized by University of Saskatchewan, *Kananaskis Short Course on Principles of Hydrology*, 28 February - 11 March 2011, University of Calgary Barrier Lake Station, Alberta, Canada.

9.2 Conference Presentations

- **Engelhardt M.**, Schuler T. V., Kjøllmoen B. (2010): Can meteorological data from SeNorge be used as input for mass balance modelling on Norwegian glaciers?
  – *International Glaciological Society Nordic Branch Meeting 2010*, 28-30 October 2010, Copenhagen, Denmark.

- **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2011): Validation of gridded precipitation maps using mass balance measurements from glaciers in Norway
  – *European Geosciences Union (EGU) General Assembly 2011*, 03-08 April 2011, Vienna, Austria.

- **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2011): Evaluation of gridded precipitation using glacier mass-balance measurements
  – *International Glaciological Society Nordic Branch Meeting 2011*, 27-29 October 2011, Oslo, Norway.

- **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2012): Runoff modelling and the contribution of glacier melt to the discharge for Nigardsbreen and Storbreen, Norway
  – *International Glaciological Society Nordic Branch Meeting 2012*, 25-27 October 2012, Stockholm, Sweden.

- **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2013): Modelling the contribution of snow and glacier melt to the discharge for highly glacierized catchments in Norway
  – *European Geosciences Union (EGU) General Assembly 2013*, 07-12 April 2013, Vienna, Austria.

- **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2013): Contribution of snow and glacier melt to the discharge for highly glacierized catchments in Norway
  – *International Glaciological Society (IGS) Conference: International Symposium on Changes in Glaciers and Ice Sheets: observations, modelling and environmental interactions*, 28 July - 02 August 2013, Beijing, China.

9.3 Conference Posters

- **Engelhardt M.**, Schuler T. V., Andreassen L. M. (2012): Mass-balance modeling of Norwegian mountain glaciers using gridded meteorological data
  – *International Glaciological Society (IGS) Conference: International Symposium on Glaciers and Ice Sheets in a Warming Climate*, 24-29 June 2012, University of Alaska Fairbanks, USA.

- **Engelhardt M.**, Schuler T. V., Andreassen L. M., Giesen R. G. (2012): Evaluating glacier melt models of different complexities and data sources - case studies at Storbreen and Nigardsbreen, Norway
  – *American Geosciences Union (AGU) Fall Meeting 2012*, 03-07 December 2012, San Francisco, USA.

Mass-balance modeling of Norwegian mountain glaciers using gridded meteorological data

Markus Engelhardt[1], Thomas V. Schuler[1], Liss M. Andreassen[2]

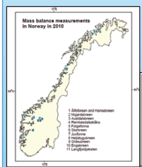
UiO : Universitetet i Oslo

[1]Department of Geosciences, University of Oslo, Norway
[2]Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway

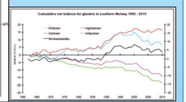
SVALI

Motivation

- Glaciers are a sensitive climate indicator
- High spatial and temporal variability of glacier mass balance in Norway
- Norway's energy production is almost exclusively based on water power (of which ca. 15 % is dependent on glacier runoff)



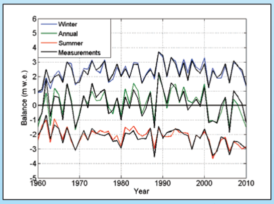
Locations of glaciers with mass-balance measurements in 2010 (from Kjøllmoen et al., 2011).



Cumulative annual balance for five glaciers in southern Norway (from Kjøllmoen et al., 2011).

Methods

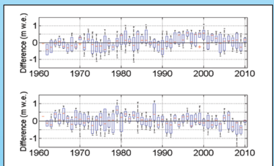
- Correcting the precipitation input (two precipitation gradients) to yield agreement between modeled and observed winter mass balances
- Optimizing a melt factor and two radiation coefficients (for potential solar radiation) to the corresponding summer mass balances
- Implementing of a weighting factor depending on the surveyed glacier area



Modeled versus measured seasonal and annual mass balance for the surveyed glacier area of Norway.

Optimized parameter set

- Precipitation gradients
  0-1000 m a.s.l.: 6.2 %
  > 1000 m a.s.l.: 14 %
- Melt factor: 1.4 mm K^{-1} d^{-1}
- Radiation coefficients
  snow: 11 mm K^{-1} d^{-1} kW^{-1} m^2
  ice: 15 mm K^{-1} d^{-1} kW^{-1} m^2



Uncertainties of the annual model results based on glacier-wide differences.

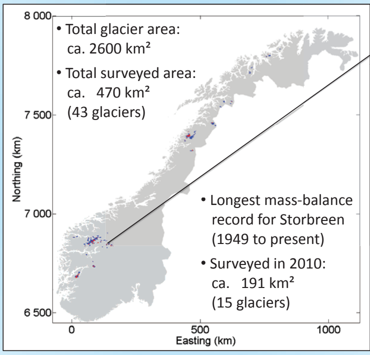
Input

SeNorge

- *SeNorge*'s temperature and precipitation data are interpolated station measurements on a 1 km grid from 1957 to present at daily time step
- Advantage: gridded input data
- Disadvantage: uncertainty between stations, especially in high altitudes

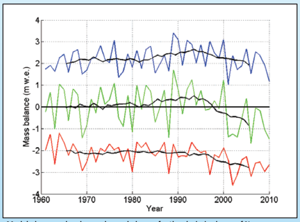
seNorges's website (http://senorge.no)

Glacier area of Norway



Blue: Location of glaciers in Norway.
Red: Location where direct mass balance measurements have been performed.

Glacier mass balance of Norway 1961–2010



Modeled seasonal and annual mass balances for the glacierized area of Norway with 10-year central moving average.

Main results

- Large year-to-year variability of seasonal and annual balances
- No clear trend in winter balances during the 1960s and 1970s, followed by an increase during the 1980s and early 1990s, and a decrease afterwards
- No trend in summer balances between the 1960s and 1990s, followed by a decrease in the same range as for winter balances

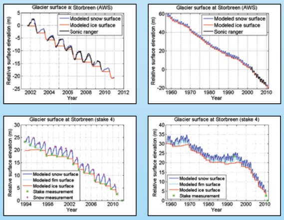
→ Slightly increase of annual mass balance between 1980 and 2000 and remarkable decrease afterwards

Case study – Storbreen

- Small mountain glacier (5.1 km²) in central southern Norway

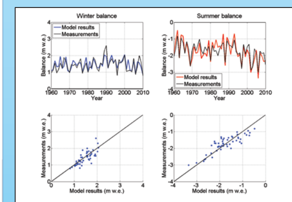
Automatic weather station and tripod at Storbreen at about 1570 m a.s.l. (from Andreassen et al., 2011).

Continuous mass-balance modeling at two point locations at Storbreen, with locally optimized degree day factors:



Stake No. 4 is located at 1725 m a.s.l.

Seasonal mass balance modeling for Storbreen:



Seasonal balances for Storbreen with optimized precipitation correction factor and optimized degree day factors.

Conclusion / Outlook

- The gridded input data together with the optimized parameter set are suitable to provide an overview of temporal evolution of glacier mass balance in Norway
- Further validation data available at Nigardsbreen from
  - sonic ranger on the glacier tongue
  - discharge measurements

Nigardsbreen, western Norway

Selected references

[1] Mohr M (2008): New Routines for Gridding of Temperature and Precipitation Observations for "seNorge.no". – Norwegian Meteorological Institute (met.no) note no. 08/2008, 40 pp.
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Acknowledgements

The authors want to thank the glacier group of the Norwegian Water Resources and Energy Directorate (NVE) for stake data. We also to thank Matthias Mohr from the Norwegian Meteorological Institute for providing further information about *seNorge*. The authors also thank all staff of NVE and Statkraft contributing in collecting and providing data for this study.
This poster is a contribution of the Nordic Center of Excellence SVALI, "Stability and Variations of Arctic Land Ice", funded by the Nordic Top-level Research Initiative (TRI).

Evaluating glacier melt models of different complexities and data sources – case studies at Storbreen and Nigardsbreen, Norway

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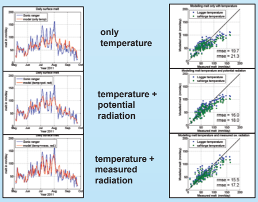
[1]Department of Geosciences, University of Oslo, Norway
[2]Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway
[3]Institute for Marine and Atmospheric Research, Utrecht University, Netherlands

"Stability and Variations of Arctic Land Ice"

Nigardsbreen

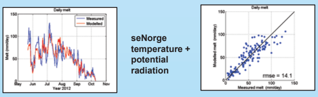
- Outlet glacier of Jostedalsbreen in western Norway
- Covers an area of 47.2 km²
- Extends from 320-1956 m a.s.l.
- Mass-balance and discharge measurements available from 1962 to present

Modeling daily melt rates for the melt season 2011, using



Validation of degree-day factors

for the melt season 2012:



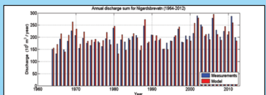
Measurements and modeling of daily melt rates for logger position at 600 m a.s.l., for the period from 21 May to 13 October 2012 (data gap of 10 days in the measurements).

Measurements and modeling of accumulated daily melt rates for logger position at 1000 m a.s.l., for the period from 23 May to 15 August 2012.

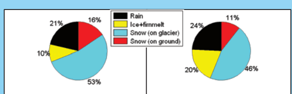
→ good fit of accumulated melt
(with the assumption of a snow density of 450 kg/m³)

Validation of melt parameters with discharge data

- Catchment for Nigardsbrevatn: 64 km²
- Glacier coverage: 75 %
- Discharge measurements available: 1962-present



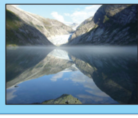
Modeled annual discharge sums for the basin of Nigardsbreen.



Relative contribution to discharge for the basin of Nigardsbreen.

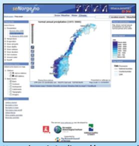
Motivation

- Glaciers are a sensitive climate indicator
- High spatial and temporal variability of glacier melt and discharge in Norway
- Need for understanding of melt processes
- Norway's energy production is almost exclusively based on water power (of which ca. 15 % is dependent on glacier runoff)



SeNorge

- *SeNorge*'s temperature and precipitation data are interpolated station measurements on a 1 km horizontal grid from 1957 to present at a daily time step



seNorges's website (http://senorge.no)

- Advantage: gridded input data
- Disadvantage: uncertainty between stations, especially in high altitudes

Conclusion

- The gridded temperature data of seNorge yields similar modeled point melt as measured temperature at logger position
- Implementation of potential solar radiation slightly improves the model results
- Modeled discharge data show increased icemelt for recent years but also a large year-to-year variability

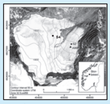
Outlook

- Implementing and optimizing of discharge routing in order to model daily discharge values
- Sensitivity analysis of melt and discharge to temperature and precipitation changes

Nigardsbreen, western Norway

Storbreen

- Small mountain glacier (5.1 km²) in central southern Norway

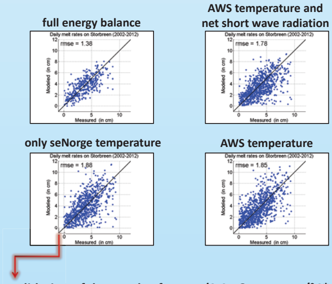


Location of stake 2 and automatic weather station at Storbreen (from Andreassen et al., 2008).

operating since fall 2001

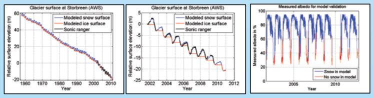
Automatic weather station and tripod at Storbreen at about 1570 m a.s.l. (from Andreassen et al., 2011).

Modeling daily melt rates for the period 2002-2012, using

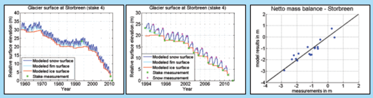


Validation of degree-day factors (3.95 & 5.15 mm/°C*d)

with continuous mass-balance modeling at two point locations:

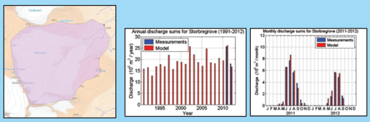


Automatic weather station (AWS) , located at 1570 m a.s.l.



Stake No. 4, located at 1725 m a.s.l.

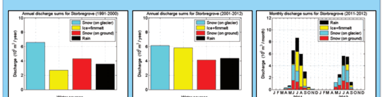
Validation of melt parameters with discharge data



Storbregrove (8.5 km²) containing Storbreen. Glacier coverage: 62 %.

Modeling annual discharge sums for 1991-2012.

Modeling monthly discharge sums for 2011-2012.



Modeled discharge from different water sources for the period 1991-2000 (left) and for 2001-2012 (center).
Most obvious is the increase in icemelt from the first to the second period.
However, large year-to-year variability does occur (right).

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Acknowledgements

The authors want to thank the glacier group of the Norwegian Water Resources and Energy Directorate (NVE) for stake data.
We also to thank Matthias Mohr from the Norwegian Meteorological Institute for providing further information about *seNorge*.
The authors also thank all staff of NVE and Statkraft contributing in collecting and providing data for this study.
This poster is a contribution of the Nordic Center of Excellence SVALI, "Stability and Variations of Arctic Land Ice", funded by the Nordic Top-level Research Initiative (TRI).