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Effect of climate change on soil temperature and snow dynamics in Swedish boreal forests

Klimatförändringars effekt på snödynamik och marktemperatur i svensk nordlig skogsmark

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Gunnar Jungqvist

ABSTRACT

Effect of climate change on soil temperature and snow dynamics in Swedish boreal forests

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This thesis has investigated the possibility of improved soil temperature modeling using an updated version of an existing soil temperature model frequently used in catchment scale biogeochemical modeling. Future (2061-2090) snow dynamics and soil temperature was projected using ensemble of bias-corrected regional climate models (RCM). Effects over a north-south gradient of Sweden were analyzed using the four Swedish Integrated Monitoring (IM) catchments as study sites. Model calibration was applied on the study sites using daily observations of soil temperature for 1996-2008.

The calibrated models were able to simulate soil temperature at different depths in the soil profile in a very accurate way in all IM sites. The lowest validation NS-value (objective criterion used for measuring goodness of fit) recorded in the study was 0.93. Even though the overall model performances were good, the simulations had problem of duplicating some of the winter temperatures at the northernmost site, Gammtratten. Whether the updated soil temperature model offered an improvement of the existing model is therefore debatable.

The future simulations showed increasing soil temperatures at all study sites on annual basis, more in the south than in the north. Annual soil temperatures were projected to increase by 1.31 – 2.33 °C for the different study sites. Winter soil temperatures were clearly higher than during 1996-2008 for the two southernmost sites, whilst Gammtratten in the north, had colder winter soil temperatures. At the midmost catchment, winter soil temperatures were quite similar to that of the test period. Whether the cold winter soil temperatures at Gammtratten were a result of snow loss was ambiguous. The results from the future simulations showed the complexity of predicting soil temperature and strengthened the conclusion among scientists that any general assumptions of future soil temperature based on e.g. air temperature cannot be done.

Key words: Impact modeling, climate change, soil temperature, snow dynamics, ensemble projections

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REFERAT

Klimatförändringars effekt på snödynamik och marktemperatur i svensk nordlig skogsmark

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Det här examensarbetet har undersökt möjligheterna till förbättrad modellering av marktemperaturer genom införandet av en uppdaterad version av en tidigare modell, frekvent använd vid biokemisk modellering på avrinningsområdesnivå. Vidare har framtida (2061-2090) snödynamik och marktemperaturer simulerats genom att en ensemble av bias – korrigerad klimatdata används för att driva modellen. Nutida (1996-2008) klimatdata, samt marktemperatursdata för kalibrering och validering av modellen, tillhandahölls från de fyra platser som ingår i det Svenska miljöövervakningsprogrammet (IM). Dessa platser kom att utgöra en syd-nordlig gradient, längs vilken resultaten analyserades.

Det generella omdömet från kalibreringen av modellen var att den kunde erbjuda en bra representation av verkliga förhållanden i fråga om marktemperatur. Det lägsta NS-värdet (objektivt kriterium använt för att mäta modellens passningsgrad) som uppmättes under valideringen var 0,93, vilket ansågs vara mycket högt. Dock hade modellen svårigheter att efterlikna verkliga markförhållanden vid Gammtratten under vintermånaderna, vilket föranledde slutsatsen att vidare undersökningar behöver göras för att kunna fastställa om modellen utgör en förbättring av den tidigare existerande versionen.

De framtida simuleringarna visade högre årliga marktemperaturer i jämförelse med dagen värden, särskilt i söder. Baserat på simuleringarna är det troligt att framtida marktemperaturer kommer att vara mellan 1,31 och 2,33 °C högre än idag. Beträffande säsongsmässig variation var maktemperaturerna under vintern högre än dagens värden för de två sydliga platserna medans de var lägre för den nodligaste platsen (Gammtratten). Huruvida de kallare simulerade marktemperaturerna vid Gammtratten var en konsekvens av ett mindre isolerande snötäcke var tvetydigt. Resultaten från de framtida simuleringarna har visat på komplexiteten i att förutspå framtida marktemperaturer och har stärkt uppfattningen om att några generella slutsatser om vad t.ex. högre lufttemperaturer kommer få för konsekvenser för framtida marktemperaturer inte kan göras.

Nyckelord: Ekosystemmodellering, klimatförändringar, marktemperatur, snödynamik

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PREFACE

This master thesis has been the final and examining part of the master programme in Aquatic and Environmental Engineering at Uppsala University. The thesis was initiated and supervised by Dr. Stephen Oni at The Swedish University of Agricultural Sciences, Department of Aquatic Sciences and Assessments. Subject reviewer of this thesis has been Dr. Martyn Futter also at the Department of Aquatic Sciences and Assessments, Swedish University of Agricultural Sciences.

First and foremost and I would like to thank my supervisor Stephen Oni who has done a tremendous job with guiding the work along the way, contributing with helpful inputs on the scientific writing process, presenting results etc.

Furthermore I would like to thank my subject reviewer Dr. Martyn Futter who has been helping providing data and software, reviewing the work and being supportive on the work progress.

Finally I would like to express my gratitude to Dr. Claudia Teutschbein at the Department of Physical Geography and Quaternary Geology, Stockholm University who has developed and provided the future climate data used in study. She has also provided insight in the methods of developing the future predictions which has been very useful.

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POPULÄRVETENSKAPLING SAMMANFATTNING

Klimatförändringars effekt på snödynamik och marktemperatur i svensk nordlig skogsmark

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Rapporteringar den om globala uppvärmningen görs ständigt. Forskarna är idag allt mer eniga om att det är antropogen påverkan som har bidragit till Jordens ökande medeltemperatur. Källor till denna ökning bedöms vara de ökande utsläppen av potenta växthusgaser till jordens atmosfär. Genom utsläppen har jordens energibalans påverkats genom att gaserna ändar hur solinstrålningen sprids, absorberas och reflekteras från jordytan till atmosfären. Effekterna av den globala uppvärmningen har dessvärre inte bara lett till ökande lufttemperatur. Förändrade nederbördsmönster, försurning av sjöar och hav mm är andra effekter som har observerats. Uppvärmningen är inte heller jämt fördelad över jordytan, ökningen har varit större på nordligare breddgrader och denna trend tror man ska fortsätta. Trots att lufttemperatur och nederbörd är viktiga klimatvariabler i sin egen rätt är dem också viktiga eftersom dem fungerar som drivvariabler till andra mekanismer. Marktemperatur har påvisats vara minst lika viktigt för biokemiska processer i marken, längden på växtsäsongen mm. Trots marktemperaturens stora inverkan har den länge varit förbisedd i forskningen på ekosystems påverkan av global uppvärmning. Vidare har forskning i Kanada visat att lufttemperatur och marktemperatur kan skilja sig markant från varandra, särkilt under vintermånaderna. Hur framtidens lufttemperatur och nederbördsmönster kommer att se ut kommer ha stor effekt på marktemperaturen eftersom snön isolerar marken från den kallare luften, vilket i vissa fall till och med kan leda till kallare marktemperaturer som ett resultat av mindre snö. Marktemperaturen styr också nedbrytarnas aktivitet i marken. Förändringar i marktemperaturer som en följd av global uppvärmning kan påverka nedbrytningshatigheter av organiskt bundet kol, och på det sättet bidra till en accelererande effekt av den globala uppvärmningen. Korrekt modellering av marktemperatur är såldes också väldigt viktigt för att kunna bedöma kolets kretslopp i marken, och dess roll i den globala uppvärmningen.

Detta examensarbete har syftat till utforska om förbättrade marktemperatursmodelleringar skulle kunna genomföras genom att använda en utvecklad variant av en befintlig marktemperatursmodell, ofta använd inom biokemisk modellering på avrinningsområdesnivå. Vidare har framtida snödynamik och marktemperaturer studerats för fyra avrinningsområden längs en syd-nordlig gradient i Sverige.

Nutida klimatdata för att driva modellen, samt marktemperatursdata för kalibrering och validering av modellen hämtades från de fyra platser (Aneboda, Gårdsjön, Kindla och Gammtratten) som ingår i det Svenska miljöövervakningsprogrammet (IM). Dessa platser kom också att utgöra den syd-nordliga gradienten. För att uppskatta framtida (2061-2090) marktemperatur användes tillhandahållen framtida klimatdata, framtagen för att erbjuda prediktioner av nederbörd och lufttemperatur för de fyra IM-platserna. Prediktionerna utgjordes av 15 olika framtida scenarier av nederbörd och lufttemperatur för varje IM-plats.

Den utvecklade modellen som användes i detta examensarbete använder lufttemperatur och nederbörd som drivvariabler, samt några markvariabler som kalibreras av användaren. Den tillåter också, tillskillnad från tidigare version, värmeflöde underifrån. Platsspecifik kalibreringen av marktemperatursmodellen gjordes med hjälp av Monte Carlo simuleringar, och kompletterande manuell kalibrering. Modellens osäkerhet bedömdes med hjälp av distributionsplottar från Monte Carlo simuleringarna. I brist på mätdata av snödjup kalibrerades inte den kopplade snömodellen utan litteraturvärden användes för att simulera snödjupet. De framtida klimatprediktionerna användes sedan som drivvariabler för modellen för att simulera framtida snödynamik och marktemperatur.

Resultatet från kalibreringen och validering av den föreslagna marktemperatursmodellen var mycket tillfredställande. Modellen klarade generellt sett av att efterlikna de uppmäta martemperaturerna som användes som kontroll. Vid den nordligaste av mätplatserna (Gammtratten) observerads vissa svårigheter att simulera vinter marktemperaturer, särskilt under de perioder då marken kyls av (höstkanten) och värms upp (vårkanten). På grund av detta kunde det med säkerhet inte fastställas att den utvecklade modellen utgjorde en förbättring av den tidigare existerande modellen. Dock var det generella omdömet att modellen kan erbjuda en bra representation av verkliga förhållanden i fråga om marktemperatur och kan implementeras i andra typer av mer avancerade biokemiska markmodeller. Vid simulering av framtida förhållanden konstaterades att både lufttemperaturen och marktemperaturen kommer att öka markant på årlig basis. Detta resultat var genomgående för samtliga mätplatser. I genomsnitt för kommer luttemperaturen att öka med ca 2,6 °C och marktemperaturen med ca 1,6 °C. I fråga om marktemperatur visade simuleringarna att avvikelserna från dagens värden var som störst längst i söder (Aneboda) och ganska lika för de andra mätplasterna. I fråga om lufttemperatur var förhållandena omvända, där var avvikelsen störst i norr (Gammtratten). Simuleringarna visade, beträffande säsongsmässig variation, att marktemperaturerna kommer att öka mest under sommar och vinter för de sydligaste två mätplatserna. I mitten av landet (Kindla) ökande temperaturen ganska jämt fördelat under året, men inget under vintern. I norr (Gammtratten) var framtidens somrar varmare men vintermarktemperaturerna lägre än dagens värden. Nederbörden var för alla mätplatser var högre under vintermånaderna men bara i Gammtratten genererade detta generellt sett mer snö. Det fanns dock stora avvikelser mellan de olika prediktionerna.

Forskningen är splittrad i fråga om vad global uppvärmning kommer att få för konsekvenser i nordliga breddgrader. Komplexiteten är stor eftersom varmare temperaturer ofta förutspås följas av mer nederbörd. Frågan är då om detta kommer att innebära mer eller mindre snö. Bidrar till komplexiteten gör också att snö isolerar marken från värmeförlust under vintern och att mindre snö kan innebära paradoxen av kallare marktemperaturer trots varmare lufttemperaturer.

Detta examensarbete har stärkt den uppfattningen och att generella slutsatser om vad varmare lufttemperatur kommer att innebära för marktemperaturen under vintern inte kan dras. Dock konstateras att de års mässiga marktemperaturerna kommer att bli högre vilket kan kunna komma att ha konsekvenser för omsättningen av kol, näringsämnen mm i marken.

Table of Contests

1 INTRODUCTION

There is increasing consensus among researchers that the world climate is getting warmer in comparison to pre-industrialized times (IPCC, 2007; Oreskes, 2004). This conclusion is supported by a growing number of observations of increasing air and water temperatures (Austin et al., 2007; Oni et al., 2013), rising sea levels (Church and White, 2006), melting of ice and snow in arctic regions (Brown, 2000; Stone et al., 2002) amidst other signals. The widely observed warming of the earth since pre-industrialized times has been proven to be connected to human activities leading to increases in the concentrations of greenhouse gases (GHGs) in the atmosphere far beyond pre- industrialized levels. For example, burning of fossil fuels has been noted to increase the emissions of GHGs to the atmosphere. The concentrations of potent GHGs, with the most important ones being carbon-dioxide (CO_2), methane (NH_4), nitrous-oxide (N_2O) and halo-carbonates (fluorine, chlorine etc.), in the atmosphere are drivers of climate change. This is because the increasing concentrations of GHGs in the atmosphere alter Earths energy balance due to changes in the absorption, scattering and emission of solar radiation in the atmosphere (IPCC, 2007). Out of 29 000 observation series from 75 independent studies, International Panel on Climate Change (IPCC) showed that significant changes in biological or physical systems can be linked to a response of a warming climate in 89% of the studies (IPCC, 2007). Their effects of global warming are not limited to increasing air temperature alone but can also be attributed to precipitation patterns as well as influencing acidification of marine and fresh water aquatic systems (IPCC, 2007).

The effects of global warming are not equally distributed throughout the globe. The effects have been greater in northern latitudes countries than the global average, and this trend might continue in the future (IPCC, 2007). Studies have shown that changes in air temperature and precipitation will be greater in northern regions, especially during the winter (Andréasson et al., 2004; Rummukainen, 2003; Vincent and Mekis, 2006). The understanding of regional variations in air temperature and precipitation due to a global climate change will be of uttermost importance in trying to predict what consequences climate change might have on soil and aquatic biogeochemical processes.

Despite their importance in controlling watershed biogeochemistry and hydrology, soil temperature data are less utilized in environmental modeling unlike atmospheric temperature. While air temperature and precipitation are important drivers of global climate change, soil temperature will have huge impact on biogeochemical processes (e.g. Haei et al., 2013), length of growing season (Domisch et al., 2001) etc. Recent research in boreal regions in Canada have shown that soil temperature may differ from that of air temperature in very complex ways (Zhang et al., 2005). The seasonal distribution of changes in temperature and precipitation patterns will have consequences on snow cover, snow density and snow durations (Zhang et al., 2005). Due to the insulating effect of the snow, the timing and intensity of snowfall will have large effect on the soil temperature especially in the winter and spring seasons (e.g. Mellander et al., 2007). Literature shows that increasing air temperatures during the winter can lower soil temperatures because of the deepening effects of frost resulting from less snow (Stieglitz et al., 2003, Brown et al., 2011).

The timing of soil warming controls the length of the growing season and plants' assimilation of nutrients (Jarvis and Linder 2000). Literature suggests that lower soil temperatures may result in increasing fine roots mortality and advancing soil leakage of nitrogen and phosphorus (Fitzhugh et al., 2001).

Soil temperature also has a profoundly ecological role by affecting microbial activities in the soil (Haei et al., 2013; Kreyling et al., 2013). Changes in soil temperatures resulting from changing snow cover and snow duration can alter microbial respiration and may lead to increasing CO_2 emissions from the soil (Goulden et al., 1998). A global soil warming of earth's permafrost regions might in that case result in a positive feedback to climate change (Davidson and Janssens, 2006). Studies have shown that the relative stability in carbon balance in northern boreal forests could shift the balance from being a carbon sink to a source of carbon with changes in soil temperature (Lindroth et al., 1998).

Therefore, there is increasing need to properly simulate soil temperature in order to address the uncertainty in simulating the changing carbon and other carbon-dependent pollutant dynamics especially in the winter (Futter et al., 2011). This thesis will explore the possibilities of improved soil temperature modeling by extending a version of an existing soil temperature model (Rankinen et al., 2004a) frequently used in catchment scale biogeochemical modeling (Futter et al., 2007; Oni et al., 2011). This thesis will address the question of how future climate change could affect the soil temperature and snow dynamics in four Integrated Monitoring sites (IM), aligning in south-north gradient of Sweden. The modeling exercise will take place at a number of different depths in the soil profile using different thermal conductivity. The objectives of the thesis can by summarized by the following milestones:

- Collect and analyze present and future driving variables data (air temperature and precipitation)
- Conduct site-specific soil temperature model calibration for the four IM sites, using several depths in the soil profile and perform general uncertainty analyses of the model parameters
- Making future soil temperature predictions by running future climate scenarios on the site-specific calibrated soil temperature models
- Analyze simulation results in comparison to present day data and make comparisons over the south-north gradient

1.1 DELIMITATIONS

Within the limitations of this thesis climate change projections will not be developed by the author. For making future prediction of snow dynamics and soil temperature driving variables data (air temperature and precipitation) will be provided for each study site. Also, the effect of changes in soil temperature on other variables, such as changes in microbial activity or changes in nutrient fluxes will not be investigated thoroughly.

2 METHODS AND MATERIALS

2.1 STUDY SITES

This thesis project was conducted in the Swedish Integrated Monitoring sites (IM); Aneboda, Gårdsjön, Kindla and Gammtratten catchments (Figure 1), set up for studying the impacts of airborne pollutions in Forest ecosystem (Löfgren, 2012).

The Swedish IM is one of the six International Cooperative Programmes (ICP) initiated by United Nation Economic Commission for Europe (UNECE). The main purpose of setting up integrated monitoring across Europe was to collect long time series of data on a number of key ecosystem variables. This has helped to study long term changes in fundamental catchment processes over climatic and deposition gradient of Sweden. This was achieved due to the relative pristine state of the catchments and long term absence of anthropogenic activities such as forestry operations and agricultural practices (Grandin, 2011).

As a result of the pristine state of the catchments, well-defined catchment boundaries and the availability of long time series of climate data, IM catchments are suitable for the modeling exercise presented in this study.

2.1.1 Aneboda

Aneboda catchment (0.189 km^2) is situated in the Småländska highlands (57^{o}07’N, 14^{o}03’E) (Table 1). The vegetation cover is dominated by Norway spruce (73%) with some Birch presence (20%). Other forest covers that are slightly represented in the catchment include Pine (3%), Beech (1%) and Alnus (2%) (Löfgren et al., 2011). Glacial till dominates the soil types with the proportion of wet soils amounting to 17% on granite bedrock. In 2005, the catchment was hit by a severe storm and was followed by bark beetle infestation that caused huge damage to the vegetation (Löfgren et al., 2011).

2.1.2 Gårdsjön

Gårdsjön catchment (58^{o}03’N, 12^{o}01’E) is located in Bohuslän in the Swedish west cost approximately 10 km from the sea (Table 1). The catchment (0.04 km^2) is the smallest of all the four IM catchments. The vegetation cover is dominated by Norway spruce (65%) but Birch (14%) and Pine (17%) are also present. The catchment geology also consists of granitic bedrock underlying glacial till soils. Soils in Gårdsjön are very shallow and interrupted by bedrock outcrops in some part of the catchment. The proportion of wet soils within the catchment is 10% (Löfgren et al., 2011).

Figure 1 Locations of the IM study sites

2.1.3 Kindla

Kindla is situated in Örebro län (59°45'N, 14°54'E), towards the middle of the country (Table 1). The catchment is quite steep with elevation ranging from 100 - 400 meters above sea level (m a.s.l.) with significant outcrops of bedrock (~41%). Catchment vegetation cover is dominated by Norway spruce and has highest percentage (83 %) of all the IM catchments used in this study. Also, Birch (14 %) and Pine (2%) are found in the catchment. The soil consists of 24 % wet soil with the presence of mire in the center of the catchment (Löfgren et al., 2011).

2.1.4 Gammtratten

Gammtratten catchment is the northernmost (63°51'N, 18°08'E) and largest (0.396 km^2) of all the IM catchments (Table 1). Gammtratten is situated in Västernorrlands län. The vegetation mainly consists of Norway spruce (70 %), with elements of Birch (16%) and Pine (13%) presence. The catchment area covers an altitude of 135 m. Pines are mostly found in the higher elevated part of the catchment, there is also presence of small mires landscape element in the upper reaches. The percentage of wet soils was 16% with presence of granite bedrock the glacial till soil type (Löfgren et al., 2011).

Table 1 Ecosystem characteristics of the IM study sites

Parameter	**Aneboda**	**Gårdsjön**	**Kindla**	**Gammtratten**
International IM-(IM ICP) Code	SE14	SE04	SE15	SE16
Latitude (RT 90) (degrees minutes)	57°07'	58°03'	59°45'	63°51'
Longitude (RT 90) (degrees minutes)	14°03'	12°01'	14°54'	18°08'
Catchment area (ha)	18.9	3.6	20.4	39.6
Elevation (m a.s.l.)	210-240	114-140	312-415	410-545

Biome	Boreo -nemoral	Boreo-nemoral	Southern-boreal	Middle-boreal
Dominant vegetation type	Norway spruce - Vaccinium myrtillus forest	Norway spruce - Vaccinium myrtillus and mixed coniferous – Vaccinium myrtillus forest	Norway spruce - Vaccinium myrtillus forest	Norway spruce - Vaccinium myrtillus forest
Annual air temperature 1996-2008. average (max min) (C^o)	6.5 (7.5 4.3)	7.0 (7.9 5.7)	5.2 (6.0 4.1)	2.4 (1.1 3.3)
Annual air temperature trend,1996-2008 (Mann –Kendall +/- and P)	+0.008	+0.05	+0.008	+0.008
Annual precipitation 1996-2008, average (max min) (mm $year^{-1}$)	796 (995 594)	1111 (1326 827)	854 (1126 697)	579 (854 419)
Annual precipitation trend, 1996-2008 (Mann-Kendall +/- and P)	+0.06	+0.1	+0.03	+0.8

2.2 PRESENT AND FUTURE CLIMATE DATA

2.2.1 Background on the provided future climate data

Global Climate Models (GCMs)

Scenario-based Global Climate Models (GCMs) are usually used for the future climate projections (IPCC, 2007). Since the climate (temperature, winds, etc.) is a connected system in the atmosphere and extend all over the world, the GCMs operates at a global scale. GCM uses a three-dimensional scale with grid cells covering different layer in horizontal and vertical directions (Hostetler et al., 2011). The emission scenarios in the GCMs were based on assumption of future population, economic development etc. These assumptions are then translated into anthropogenic emission scenarios used as forcing for the GCMs, though different feedbacks forcing are also integrated. These feedbacks forcing include the melting of ice caps, changes in CO_2 balances in soils and ocean etc. As a result, all GCMs are designed to model the complex climatological system of Earth. This leads to differences between GCM representations of the future as a result of varied responses to forcing (Hostetler et al., 2011). For this reason, GCM may simulate quite different responses to the same forcing; simply because of differences in the way certain processes and feedbacks are modeled.

Downscaling

As GCM have global focus, their direct applications are not suitable for local impact studies. To create outputs with higher resolution, different types of GCM downscaling are usually used in the literature. Two major techniques widely used in climate impacts studies include dynamic and statistical downscaling (Wilby and Wigley, 1997). In dynamic downscaling GCM outputs are used as boundary conditions for Regional Climate Models (RCMs) with higher resolution, taking local conditions into account (Hostetler et al., 2011; Teutschbein and Seibert, 2012). In statistical downscaling, statistical methods are usually used to establish empirical relationships between equivalent of present day GCM outputs and observed climate data from local weather stations (Crossman et al., 2013; Wilby et al., 1998). Using the statistical relationships derived from the empirical relationships, local scale future scenarios can be generated from the global-scale GCM predictor variables (Oni et al., 2012).

A dynamical downscaling approach was utilized in this study. In this approach, 15 RCMs were used to transform GCM variables to higher resolution at local scale. As RCMs operate at a regional scale, there is often a mismatch in scales, especially at smaller watersheds. As a result, there are always biases between the RCMs and the site specific conditions (e.g. Christensen, et al., 2008; Teutschbein and Seibert, 2012). Commonly recorded biases are e.g. incorrect seasonal variation in precipitation and predictions of too many days with low-intensity rain (Teutschbein and Seibert, 2012). This makes bias correction to site-specific conditions an important step before RCM outputs can be used in local impact studies (Teutschbein and Seibert, 2012). In this thesis, the site specific future scenario data from RCMs were bias corrected using “distribution mapping” technique. This approach has been found to be the best bias correction method for small and meso-scale catchments in Sweden (Teutschbein and Seibert, 2012). The general idea with distribution mapping is to fit cumulative distribution functions (CDFs) of observed data to CDFs of RCM output data. For more detailed descriptions of this technique, see Teutschbein and Seibert, (2012).

The ENSEMBLES project

The ENSEMBLES is an international research project initiated by the European Commission with the aim of creating climate scenarios and to help inform decision makers, researchers, the public, businesses etc. on the latest climate modeling data (Van der Linden and Mitchell, 2009). The ENSEMBLES project gathered climate researchers from all over Europe, for the first time, to work together on this single goal (Van der Linden and Mitchell, 2009). The project was set up to run multiple of climate models (the ensembles) in order to create a range of possible climate outcomes and to make the predictions more statistically reliable. The ENSEMBLES project used several different GCMs and RCMs to create a matrix of possible predictions (Van der Linden and Mitchell, 2009).

2.2.2 Site-specific climate data

The bias corrected ensemble RCM data were used as driving variables for the prediction of future soil temperatures presented in this thesis. The data consists of 15 different climate projections of future air temperature and precipitation for the period 2061-2090. The climate data used in this thesis are a product of research efforts aiming to provide bias corrected RCM climate variables for the Swedish IM sites. Throughout this thesis, site specific bias corrected RCM outputs will be referred to as “the ensembles”, or according to their assigned number in Table 2.

The data were provided as daily time series from 2061-2090 but with 30 days in each month. Using GCM infill software (prepared as part of INCA suite of models, e.g. Whitehead et al., 1998), the series were time corrected for calendar year to facilitate coupling with soil temperature and snow model.

While conducting this study there were indications that the air temperature and precipitation data used for bias correcting the provided climate scenarios for Gammtratten were not correct. Gammtratten future snow dynamics and soil temperature were therefore simulated using bias corrected RCM climate scenarios from a neighboring catchment, Krycklan (Oni et al., 2013) with long term weather data. The weather in the two catchments is fairly similar (Figure 2 and 3), supporting the assumption of using Krycklan future scenario to drive the soil temperature model in the Gammtratten catchment.

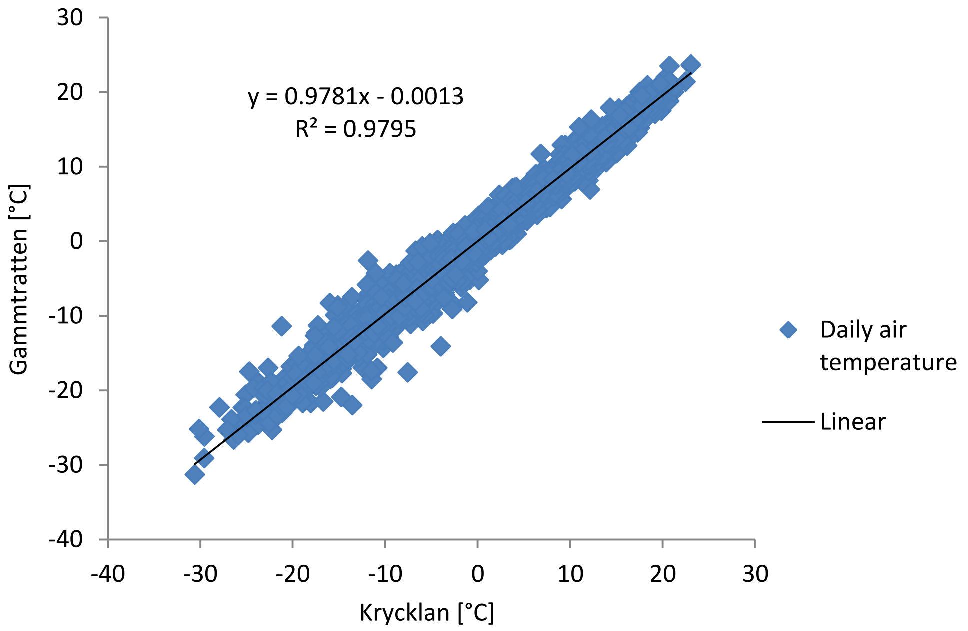

Figure 2 Daily air temperature at Gammtratten and Krycklan 1996-2008

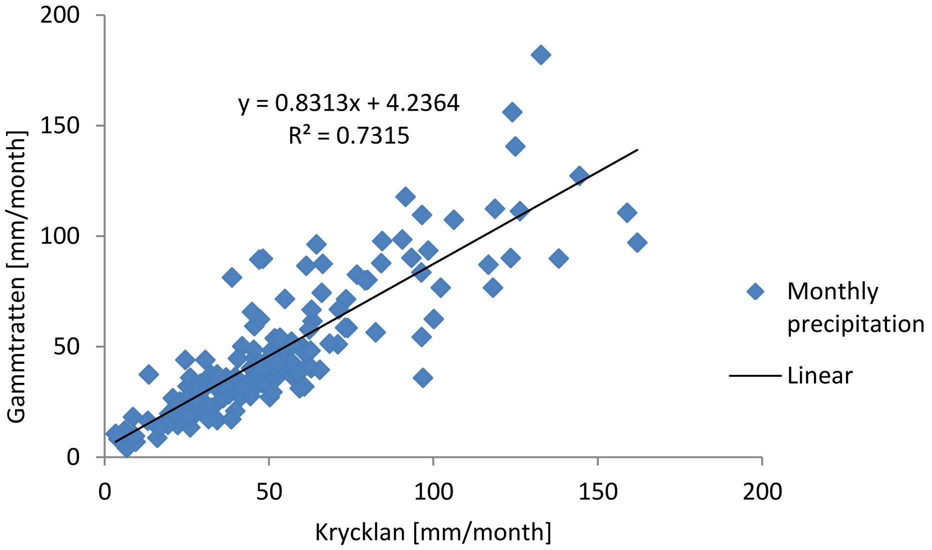

Figure 3 Monthly precipitation at Gammtratten and Krycklan 1996-2008

Table 2 Underlying RCMs for the bias corrected site-specific air climate scenarios. Their labeling, resolutions, driving GCMs, emission scenarios and performing institutes

No.	Prediction	Institute	RCM	Resolution	Driving GCM	Emission scenario
1	C41_HAD	C4I	RCA3	25 km	HadCM3Q16	A1B
2	DMI_ARP	DMI	HIRHAM5	25 km	ARPEGE	A1B
3	DMI_BXM	DMI	HIRHAM5	25 km	BCM	A1B
4	DMI_ECH	DMI	HIRHAM5	25 km	ECHAM5	A1B
5	ETHZ	ETHZ	CLM	25 km	HadCM3Q0	A1B
6	HC_HAD0	HC	HadRM3Q0	25 km	HadCM3Q0	A1B
7	HC_HAD3	HC	HadRM3Q16	25 km	HadCM3Q16	A1B
8	HC_HAD16	HC	HadRM3Q3	25 km	HadCM3Q3	A1B
9	KNMI	KNMI	RACMO	25 km	ECHAM5	A1B
10	MPI	MPI	REMO	25 km	ECHAM5	A1B
11	SMHI_BCM	SMHI	RCA	25 km	BCM	A1B
12	SMHI_ECH	SMHI	RCA	25 km	ECHAM5	A1B
13	SMHI_HAD	SMHI	RCA	25 km	HadCM3Q3	A1B
14	CNRM	CNRM	Aladin	25 km	ARPEGE	A1B
15	ICTP	ICTP	RegCM	25 km	ECHAM5	A1B

2.2.3 Present day data for model calibration

The data input requirements for the soil temperature model include observed average daily air temperature, snow depth and precipitation. Snow depth data can be either measured or modeled (Rankinen et al., 2004a). However, the snow depth data used in the soil temperature model presented in this thesis were modeled. The continuous time series of both air temperature and precipitation were provided by the IM database for each of the four IM study sites for the period 1/1/1996 - 31/12/2008. There were missing precipitation data for Aneboda on the 20th and 21st of March 2002, and 4th October 2001 for Gammtratten. In the Aneboda the precipitation was zero the following dates so the precipitation was set to zeros for 20th and 21st as well. At Gammtratten, it was raining the previous and the following day, so the missing precipitation data was substituted with an interpolated value. General data analysis was performed on the provided data (Table 1). Annual trends were calculated using Mann-Kendall two-tailed trend test (Libiseller and Grimvall, 2002).

Soil temperature data (needed for calibration and validation of the soil temperature model) were provided for different depth but three depths were chosen at each catchment (Table 3). Due to large gaps in the soil temperature data, depths with the most consistent long term series were used as calibration and validation data of the model in each catchment (Table 3).

Table 3 Catchments and there soil profile depths

Catchment	Depth in soil profile (cm)
Aneboda, top layer	10
Aneboda, middle layer	32
Aneboda, bottom layer	58
Gårdsjön, top layer	0*
Gårdsjön, middle layer	10
Gårdsjön, bottom layer	25
Kindla, top layer	5
Kindla, middle layer	20
Kindla, bottom layer	35
Gammtratten, top layer	5
Gammtratten, middle layer	29
Gammtratten, bottom layer	40

***** Simulated as 1 cm depth

2.3 SOIL TEMPERATURE MODEL

An important step in the modeling process is choosing a good model set-up (Refsgaard et al., 2007). This process includes transforming a conceptual model (based on various physical and biochemical processes) into a site-specific model. In the past, simple empirical models describing the relationship between air temperature and soil temperature, or models describing harmonic oscillations around mean temperatures has been used (Tamm 2002). Nowadays, modelers prefers using models that numerically solves partial differential equations of heat balance, coupled with numerical models of water fluxes, which give the ability to describe three-dimensional heterogeneity and temporal variations (Tamm, 2002).

2.3.1 Background on soil physics

The soil temperature model in use in this thesis was derived from two differential equations describing the combined water and heat flow in seasonally frozen soil (Karvonen, 1988). These equations were derived from the law of conservation of energy and mass (Eqns. 1 and 2) owing to the fact that water and heat spread out in the soil profiles along gradients of water potential and temperature (Darcy and Fourier laws) (Rankinen et al., 2004a).

$$C_S \frac{\partial T}{\partial t} - \rho_I L_F \frac{\partial I}{\partial t} = \frac{\partial}{\partial Z}\left[K_T(\theta)\frac{\partial T}{\partial Z}\right] - C_W q_W \frac{\partial T}{\partial Z} \qquad (1)$$

$$C(h)\frac{\partial h}{\partial t}+\frac{\rho_I}{\rho_W}\frac{\partial I}{\partial t}=\frac{\partial}{\partial Z}\left[K(h)\left(\frac{\partial h}{\partial Z}+1\right)\right]-S(h) \tag{2}$$

where Z (m) is a space coordinate, T (^{o}C) is soil temperature, K_T (Wm^{-3o}C^{-1}) is the soil thermal conductivity, L_F (Jkg^{-1}) is latent heat of fusion and water, C_S (Jm^{-3o}C^{-1}) is volumetric specific heat of the soil, ρ_I (kgm^{-3}) is density of ice, ρ_W (kgm^{-3}) is density of water, q_W (ms^{-1}) is flow of water, q (dimensionless) is volumetric water content, I (dimensionless) is volumetric ice content, h (m) is soil water potential, *C(h)* (m^{-1}) is differential moisture capacity, *K(h)* (ms^{-1}) is unsaturated hydraulic conductivity of the soil matrix and *S(h)* (dimensionless) represents the water taken up by the roots. These equations calculate water and heat flow based soil properties; the water retention curve, unsaturated and saturated hydraulic conductivity, heat capacity (including latent part during thawing/melting) and the thermal conductivity (Rankinen et al., 2004a).

2.3.2 The Rankinen model

The model used in this thesis was based on the soil temperature model described in Rankinen et al. (2004a). This model was based on simplifications of Eqns. (1) and (2), with the aim “of developing a simple but practical model for calculating soil temperature in seasonal frozen soils that can be easy to implement at a catchment scale”. The model calculates soil temperature at different depths at a daily time step, taking into account the influence of snow cover. The simplification made by Rankinen et al. (2004a) ignored the influence of changes of water content on soil temperature. This made it not necessary to solve Eqn. (2) and all water related terms from Eqn. (1) can be left out with the exception of the ice term.

The derivative of the soil thermal conductivity through the soil profile was replaced by a constant, representing the average thermal conductivity of the soil (Rankinen et al., 2004a). However, the soil thermal conductivity was linked with the soil moisture (Karvonen, 1988), which varies throughout and soil profile and throughout the seasons. As a result of this simplification, the model lost its validity on very wet or dry conditions but greatly simplified solving Eqns. (1) and (2). More detailed information about the model description and equations were described in Rankinen et al. (2004a).

Through the simplifications of Eqns. (1) and (2) the following equations for soil temperature were obtained (Rankinen et al., 2004a).

$$T_*^{t+1} = T_Z^t + \frac{\Delta t K_T}{(C_S + C_{ICE})(2Z_S)^2}\left[T_{AIR}^t - T_Z^t\right] \tag{3}$$

As eqn. (3) did not take the influence of snow into account, the equation was extended by an empirical equation that could compensate for snow cover, Eqn. (4).

$$T_Z^{t+1} = T_*^{t+1} e^{-f_S D_s} \tag{4}$$

Substituting Eqn. (3) into Eqn. (4), soil temperature could be calculated Eqn. (5)

$$T_Z^{t+1} = T_Z^t + \frac{\Delta t K_T}{(C_S + C_{ICE})(2Z_S)^2}[T_{AIR}^t - T_Z^t][e^{-f_s D_s}] \tag{5}$$

where K_T ($\mathrm{Wm^{-1}\,{}^{o}C^{-1}}$) is the thermal conductivity, C_S ($\mathrm{Jm^{-3}\,{}^{o}C^{-1}}$) is the specific heat capacity of the soil, C_{ICE} ($\mathrm{Jm^{-3}\,{}^{o}C^{-1}}$) is the specific heat capacity due to freezing and thawing (latent part) as well as f_s ($\mathrm{m^{-1}}$) which represents an empirical snow parameter. These represent model parameters that can be used in the model calibration. T_{AIR} (^{o}C) and D_S (*mm*) represent air temperature and snow depth variables.

2.3.3 Extended version

In evaluating the derivatives from Eqn. (1), boundary conditions were set as T_{SURF} (temperature at the surface, replaced by air temperature T_{AIR} in Eqn. (3)), T_Z (temperature in the soil evaluated according to space reference *Z*) and T_l which is soil temperature at $2Z_S$. For simplification purpose, this last term was assumed to equal T_Z, indicating that heat flow under the soil layer of consideration could be taken into consideration. However, this thesis tried to further explore the possibilities of improving the soil temperature simulations when the thermal conductivity is allowed to vary throughout the profile. In addition to the model parameters from Eqn. (5), this extended version also utilized temperature inputs below the soil layer of consideration. Therefore, parameters controlling the lower soil thermal conductivity $K_{T,LOW}$, lower soil specific heat capacity $C_{S,LOW}$, and lower soil temperature T_{LOW} were also added to the model (Eqn. 6).

$$T_*^{t+1} = T_Z^t + \frac{\Delta t K_T}{(C)(2Z_S)^2}[T_{AIR}^t - T_Z^t][e^{-f_s D_s}] + \frac{\Delta t K_{T,l}}{C_{s,l}2(Z_l + Z)^2}[T_l - T_Z^t] \tag{6}$$

$$C = C_S\,;\; T_Z^t > 0 \tag{7}$$

$$C = C_S + C_{ICE}\,;\; T_Z^t \leq 0 \tag{8}$$

where Z_l is a constant indicating the space coordinate from which the lower temperature influence is working.

2.4 SNOW MODEL

In this study a simple index snow model was used, based on models used by Vehviläinen (1992). Whether a certain precipitation is regarded as snowfall temperature was determined by threshold parameters T_{LOW} and T_{UP}. If the air temperature, T_{AIR} is below T_{LOW} the precipitation is snow, if above T_{UP} the precipitation is rain. If the air temperature is between those two thresholds the precipitation is considered to be partly snow and partly rain (Rankinen et al., 2004b). In case of sleet, a simple solid/wet-relationship converted parts of the precipitation to snow. A dimensionless correction factor was multiplied with the solid precipitation depending on gauge type (Rankinen et al., 2004b). Another threshold was used for snow melt. If the air temperature is above snow melt factor temperature, the snow pack and the precipitation (if it falls as snow) melt. The melting is decided by a degree day melt factor.

Water losses due to evapotranspiration were also taken into account using an evapotranspiration rate constant. The snow depth was then calculated as water equivalent of precipitation falling as snow subtracted by melting and evapotranspiration. The snow depth (as water equivalent) was then converted into snow depth by dividing with the density of the snow cover. The snow density was calculated using density of new snow and an aging factor. The aging factor compensated for the increase in the density of the snow as snow pack age and become more compact.

Since the snow model in this thesis was not calibrated, literature values were used (Table 4). Correlation factor for solid precipitation, temperature below which precipitation falls as snow, temperature above which precipitation falls as rain, temperature at which snow melts and rate of sublimation from snow were set at fixed values as used in the INCA model (Rankinen et al., 2004b). The values for Degree day melt factor, new snow density and aging factor used were listed in Table 4.

Table 4 Parameter values for the snow model

Parameter	**Unit**	**Value**
Correlation factor for soil precipitation	-	1.23
Temperature below which P falls as snow	^{o}C	-1
Temperature above which P falls as rain	^{o}C	1
Temperature at which snow melts	^{o}C	0.5
Rate of evapotranspiration from snow	$mm\ d^{-1}$	0.09
Degree day melt factor	$mm\ d^{-1}\ {}^{o}C^{-1}$	1.43
New snow density	$kg\ m^{-1}$	0.1
Aging factor	-	0.033

2.5 SOIL TEMPERATURE MODEL CALIBRATION

The calibration was done in different stages. In this first stage, soil temperature model parameters (C_S, K_T, f_S, T_{LOW}, C_{ICE}, $C_{S,LOW}$ and $K_{T,LOW}$) were calibrated for each depth in the soil profile separately. The calibration strategy was done by performing the following steps.

2.5.1 Monte Carlo analysis

Monte Carlo analysis was in this case used as an optimizing strategy in the calibration of the model as well as tracing out the structure of the model output (Refsgaard et al., 2007). Monte Carlo was based on random sampling of model parameters, followed by evaluation of the model outputs (Mooney, 1997). Therefore, use of Monte Carlo sampling strategy has been very useful in environmental models with significant uncertainty in inputs-outputs, since it allows evaluation of multiple combinations of parameters settings. By changing one parameter at the time (as usually done in manual calibration), model performance might become limited by not allowing more than one degree of freedom. However, evaluating multiple combinations of parameters manually is often impossible in more complex systems.

Identify parameter distribution and sample from distribution

The first step in the Monte Carlo analysis was to identify suitable parameter distributions. If the parameters are not constrained properly when performing Monte Carlo analysis, the outputs might give parameter values that may describe the output signal in a satisfying way. However, such parameter values might not be credible enough to provide any useful information on the system behavior (right answer for the wrong reason). It is therefore of importance that the model parameters are set within reasonably range when performing Monte Carlo analysis.

When modeling systems with parameters that have a physical interpretation (grey box modeling), Monte Carlo analysis must be combined with prior knowledge of the system. In the soil temperature model described in this paper, six out of the seven parameters have clear physical interpretations, which means that their values are limited by their physical boundaries. Choosing the parameter range for the specific study site of interest is difficult, and there is often no “true value”. However, there are number of strategies in choosing a suitable parameter range; Literature values, experimental results and measurements as well as expert judgments.

The range at which the upper soil temperature parameters (C_S, K_T, f_S and C_{ICE}) were allowed to vary was based on the parameter values used by Rankinen et al. (2004a; 2004b) and Tamm (2002). The range of the lower soil temperature parameters (T_{LOW}, $C_{S,LOW}$ and $K_{T,LOW}$) were unknown, and the range of those parameters were set according to judgments. In order to fully explore the ranges of the parameters the intervals were set quite widely in the Monte Carlo analysis (Table 5). Though using a wide parameter range generates a lot of parameter combinations that are not that useful, it ensures that the model optimum parameter space was not overlooked due to narrow intervals.

The Monte Carlo analysis was conducted by running the model 100 000 times, sampling a new set of randomized parameters for each model run from the chosen parameter ranges (Table 5). This process was repeated for each site and for all depths. The vast amount of simulations ensured that the whole parameter range was covered by the simulations. Histogram plots over the sampled parameters were used for control. Each parameter was sampled using Matlab rand command, scaled to fit each parameter range. Five significant digits were used for each parameter.

Table 5 Parameter ranges for the Monte Carlo simulations

Parameter	**Unit**	**Monte Carlo ranges**
Specific heat capacity of soil, C_S	$Jm^{-3}°C^{-1}$	0.5 – 3.5 (10^6)
Soil thermal conductivity, K_T	$Wm^{-1}°C^{-1}$	0 – 1
Specific heat capacity due to freezing and thawing, C_{ICE}	$Jm^{-3}°C^{-1}$	4 – 15 (10^6)
Empirical snow parameter, f_S	m^{-1}	0 – 10
Lower temperature, T_{LOW}	°C	0 – 1
Thermal conductivity, lower part, $K_{T,LOW}$	$Wm^{-1}°C^{-1}$	0 – 1
Specific heat capacity of soil, lower part, $C_{S,LOW}$	$Jm^{-3}°C^{-1}$	0.5 – 3.5 (10^6)

Evaluating goodness of fit

For each model run (with a new set of randomized parameters) of the Monte Carlo analysis, the resulting soil temperature was analyzed by evaluating how the model performed in relation to observed data. This is referred to as the model goodness-of-fit (Massey, 1951) with the target of getting the best values as possible. Goodness of fit can be assessed using subjective or objective criteria. In this thesis, the goodness of fit was evaluated by using the objective statistical function given by Nash and Sutcliffe (1970) in Eqn. 9.

$$NS = 1 - \frac{\sum_{i=1}^{N}\left(D_{m,i} - D_{av}\right)^2}{\sum_{i=1}^{N}\left(D_{m,i} - D_{c,i}\right)^2} \qquad (9)$$

2.5.2 Manual Calibration

Manual calibration was applied on the best simulated parameter settings from the Monte Carlo analysis. This was done in order to tune in the optimum parameter setting more carefully. NS values were studied in order to optimize the calibration.

2.5.3 Validation

To test the efficacy of the model in simulating the present day and projecting plausible future trajectory of soil temperature, model performance was validated using an independent data set. Since there were gaps in obtained data sets, the calibration and validation periods were not split by a specific date but by examining the number of data points available in the observed data and then splitting the data series in thirds. The first two third of the series were used for calibration, making the calibration and validation periods differ between catchments and soil depths (Tables A2-A5). Choosing two thirds for calibration gave enough long term series to get enough data for the calibration. Model performance during the validation periods were measured using combination of NS, R^2 (calculated based on linear fitting of observed and modeled values) and RSME, Eqn. (10).

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(D_{m,i} - D_{c,i}\right)^2}{N}} \qquad (10)$$

2.5.4 Uncertainty analysis

The model uncertainty analysis was performed by subjecting the Monte Carlo outputs to further analysis; distribution mapping and cumulative distribution frequency. The easiest way to assess information about model uncertainty is through distribution mapping (Refsgaard et al., 2007). In order to trace out the structure of the model output and evaluate the model performance, the top 5000 simulated parameter settings were plotted against NS values for each parameter. A sensitive parameter tends to skew towards either end of parameter range when the NS is high in contrast to a non-sensitive parameters distribution that spread all over parameter range.

Cumulative distribution frequency

Investigating the cumulative distribution frequency (CDF) is an analytical method providing information on how often a certain event occurs (Burr, 1942). The parameter settings for the best 100 simulations were saved (based on goodness of fit). The top 100 simulations were then ranked according to NS values and plotted (using CDF) for each parameter. This technique is very applicable in environmental modeling to evaluate the results of Monte Carlo analysis. This gives further insights on the optimum parameter spaces that can represent the system, the overall sensitivity of the parameters as well as the contrast in catchment behaviors.

In this study, CDF was performed on the behavioral parameter sets from the first iteration of Monte Carlo analysis according to *function(x)* in eqn. 11

$$F(x) = \frac{N_x}{N_{tot}} \; ; \begin{cases} N_x = number\ of\ observations \leq x \\ N_{tot} = total\ numer\ of\ observations \end{cases} \qquad (11)$$

A steep slope in the resulting curve indicates that the parameter is sensitive within that interval, as the values in that interval are frequently occurring when a good goodness of fit is recorded. A straight line in the resulting curve indicates that the parameter is not sensitive.

2.6 CLIMATE PROJECTIONS EFFECT ON FUTURE SNOW DYNAMICS AND SOIL TEMPERATURE

Projections of future snow dynamics and soil temperature were conducted by running the future climate data (Table 2) on the site-specific calibrated snow-soil temperature models. The future simulations were done for all four study sites, generating daily data series from 2061-2090 of simulated air temperature, precipitation, snow depth and soil temperature for all of the fifteen ensembles projections. Since model calibration was done at three depths (Table 3), three soil temperature data series were generated at each site for each RCM projection (air temperature, precipitation and snow depth being the same at each site). Predicting future climate and its impact on specific systems always contains uncertainties (IPCC, 2007). The main reason for simulating such a large number of projections in this study was that it addressed the importance of acknowledging those uncertainties, and that the ensemble projections presented a range of possible future outcomes.

2.6.1 Annual changes

Projected soil temperature driven by fifteen different regional climate models, at four sites and at three different depths at each site generates a vast amount of data. In order to present the variation of the ensembles of soil temperature outputs in a compact but yet representative way annual mean values were calculated for each scenario and at each depth. The median year, from the middle layer in the soil profile from the annual values were then chosen to represent each ensemble prediction. If any result from the other layers in the soil profiles differs significantly from that of the middle layer, those results will be mentioned in the result section; else the middle layer is chosen as a reference. For the simulated results for all depths, see Table B1-B4.

2.6.3 Seasonal variations

The seasonal variation in the ensembles' projected soil temperature data were compiled by calculating monthly averages for each of 15 RCMs during 2061-2090, generating one monthly average value for each projection. Maximum, median and minimum monthly outputs were then calculated based on these monthly averages (Tables B5-B8). Future snow depth was represented in the same way (Tables B9-B13).

3 RESULTS

3.1 PRESENT AND FUTURE CLIMATE DATA

In analyzing the data used for driving the snow-soil temperature model, the multi-RCM ensemble projected a range of possible future climates depending on the study site location and climate conditions. However, the overall signal was consistent in all catchments with projected increase in total annual precipitation (Figure 4) and annual mean temperature (Figure 5). In terms of seasonal changes, precipitation and temperature were projected to increase in most months of the year (Figures 4 and 5), although the change will likely be more pronounced during colder months, November to April (Table A1). Considering temperature changes, the period with temperatures below 0 °C is projected to shorten considerably in the Northern catchments (Kindla and Gammtratten) and to disappear completely in the Southern catchments (Aneboda and Gårdsjön) (Table A2). These higher temperatures will have substantial consequences on winter snow accumulation/melt and soil temperatures.

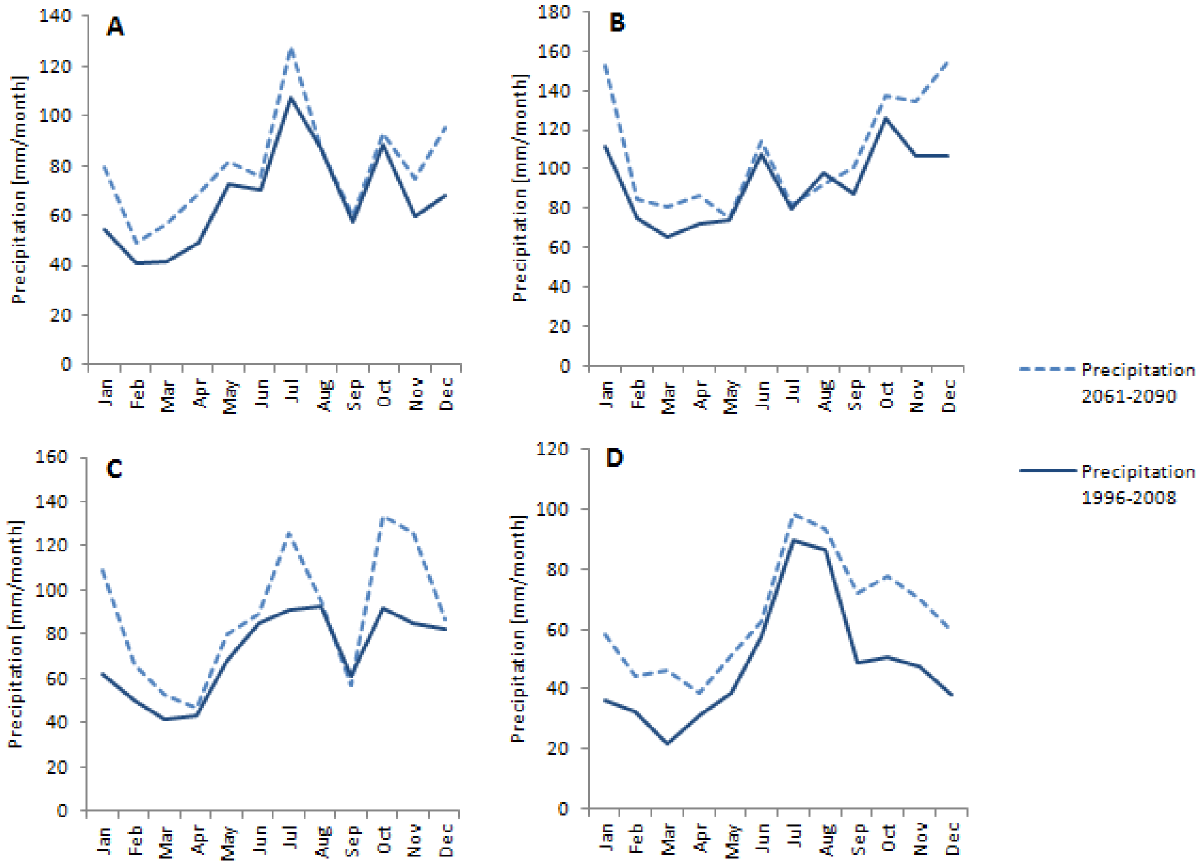

Figure 4 Monthly precipitation 2061-2090, ensambles median and monthly precipitation 1996-2008, for Aneboda (A), Gårdsjön (B), Kindla (C) and Gammtratten (D)

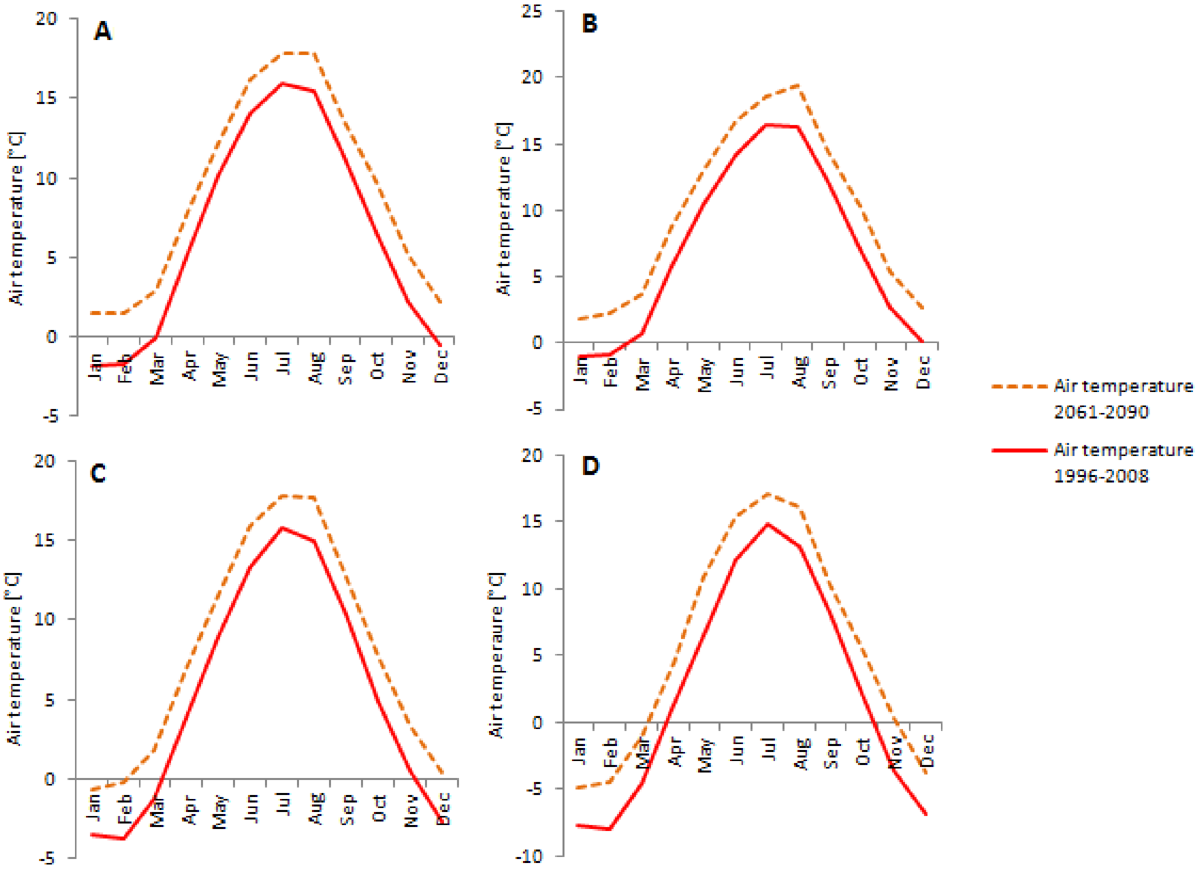

Figure 5 Monthly average air temperature 2061-2090, ensembles median and observed monthly air temperature 1996-2008, for Aneboda (A), Gårdsjön (B), Kindla (C) and Gammtratten (D)

3.2 MODEL CALIBRATION AND VALIDATION

The site-specific parameter values for the calibrated soil temperature models were within expected ranges. For full accounting on the calibrated parameter values for each site and soil profile depth, see Table A3.

3.2.1 Soil temperature model

The calibrated models well captured the inter-annual variation of soil temperature with high accuracy. For Aneboda the NS values vary from 0.958 to 0.972 for the calibration period and from 0.963 to 0.974 for the validation period (Table A4). Mean values of soil temperature from both the calibration and validation periods were simulated to a satisfying degree on all depths (Table A2). Both summer and winter extreme values were simulated well by the model (Figure 6). Model could not capture some low and high soil temperature values. The first winter of the calibration period has quite low values for the top and middle layers in Aneboda (Figure 6). These low values were not well simulated. There was a difference of 2.5 °C between simulated and observed values (Table A4). Aneboda also has some really high values, almost 15°C for the top two layers, in yearly June 1996, that were not quite captured by the model (Figure 6).

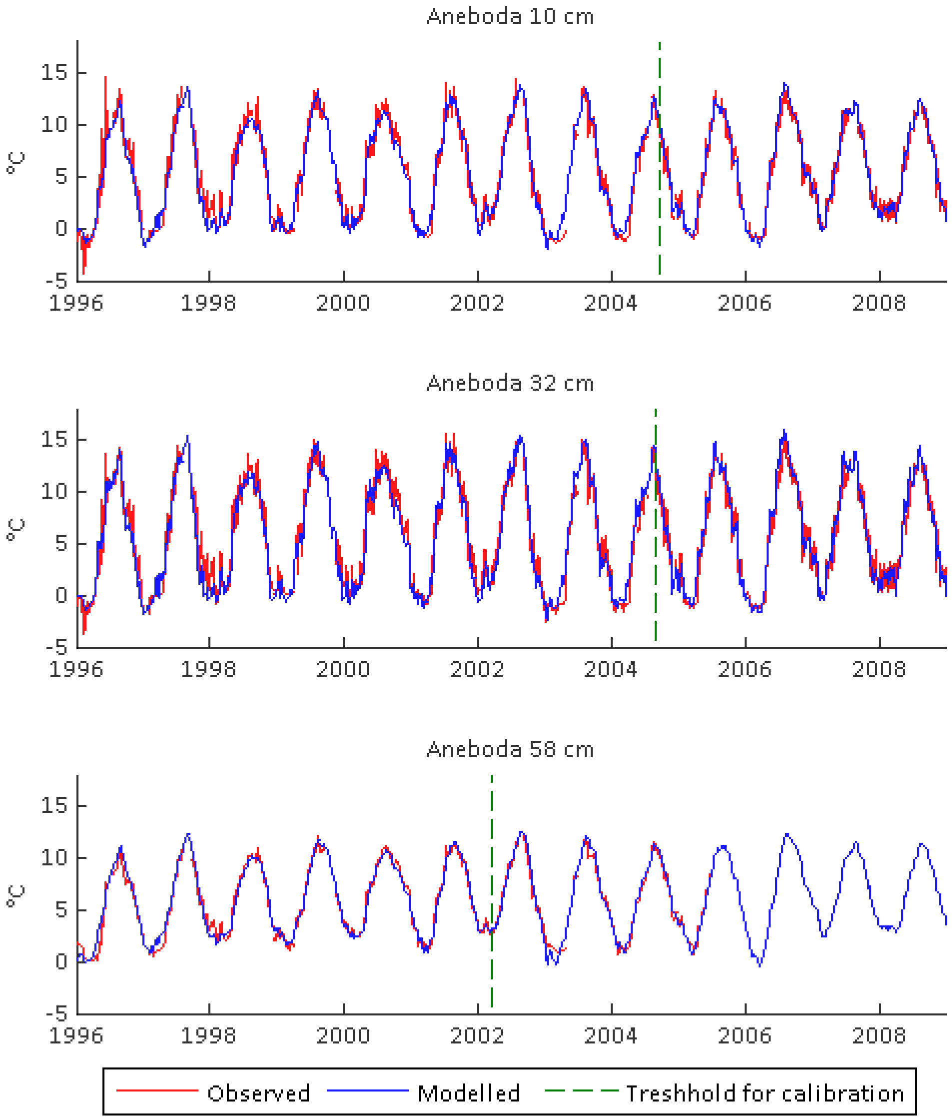

Figure 6 Simulated and observed soil temperatures for Aneboda

The simulated values for soil temperature were congruent to observed values for all depths at Gårdsjön. The NS values ranged from 0.972 to 0.988 (highest NS value recorded in the study) for the calibration period (Table A5). Lowest NS values for the validation period were 0.943 and the highest 0.963 (Table A5). Mean values, maximum values and minimum values were well simulated, with few exceptions (Figure 7). The winter of 2006 showed a dip in soil temperature at all the depths and patterns were not well captured by the model (Figure 7). Also, some extreme values for the two uppermost layers in the summers of 2000 and 2001 and winter 2003 (for the top layer) were not well captured (Figure 7).

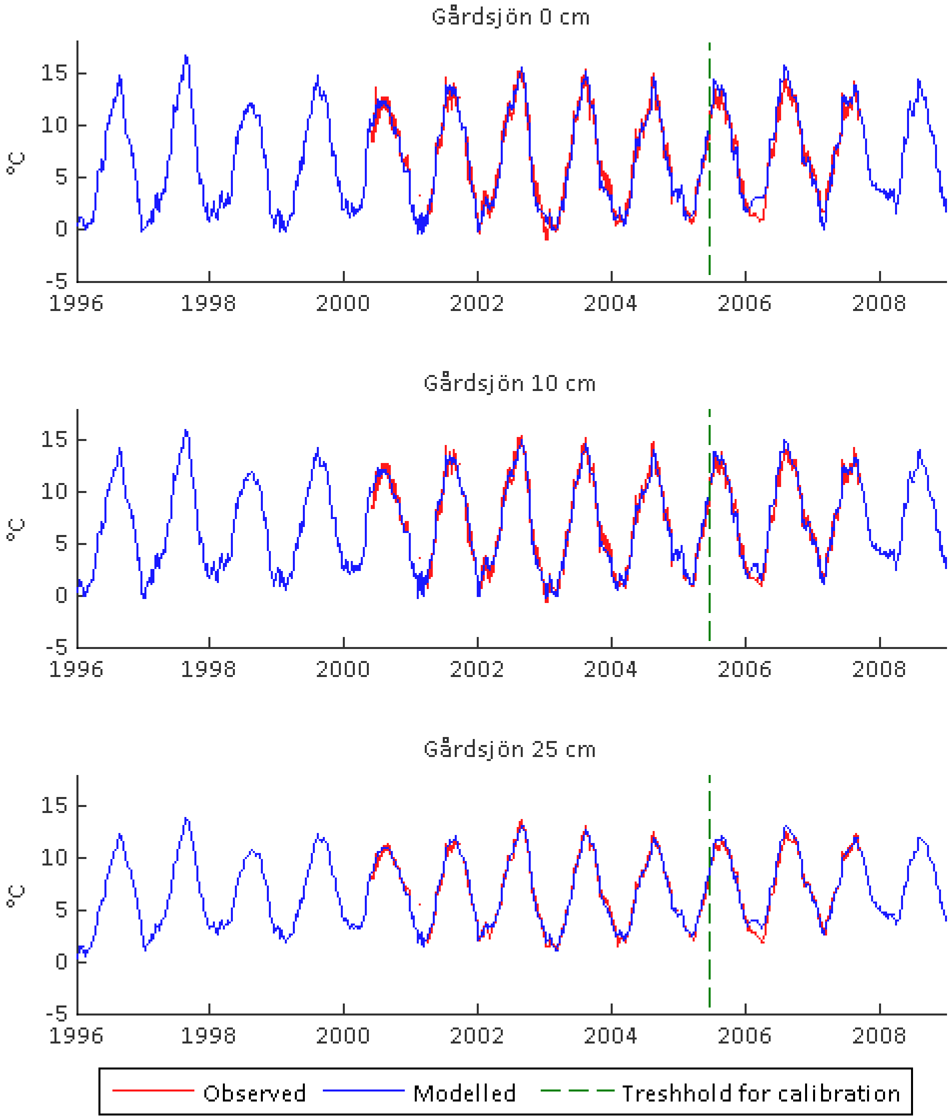

Figure 7 Simulated and observed soil temperature during 1996-2008 for Gårdsjön

Model simulations in Kindla showed NS values of 0.950 to 0.970 for the calibration period and 0.944 to 0.982 for the validation period. The goodness of fit for the bottom two layers were the highest values (both 0.982) for the validation period in this study (Table A6). The top layer was missed in February 1999, with a 2.5 °C difference between simulated and observed values at some dates. This represents the biggest difference in observed and simulated values for Kindla. During the validation period, the model overestimated the summer soil temperatures for the top most layer at some dates in the summer of 2008 with more than 1°C (Figure 8). This result also reflected the model simulations during the validation period (Table A6).

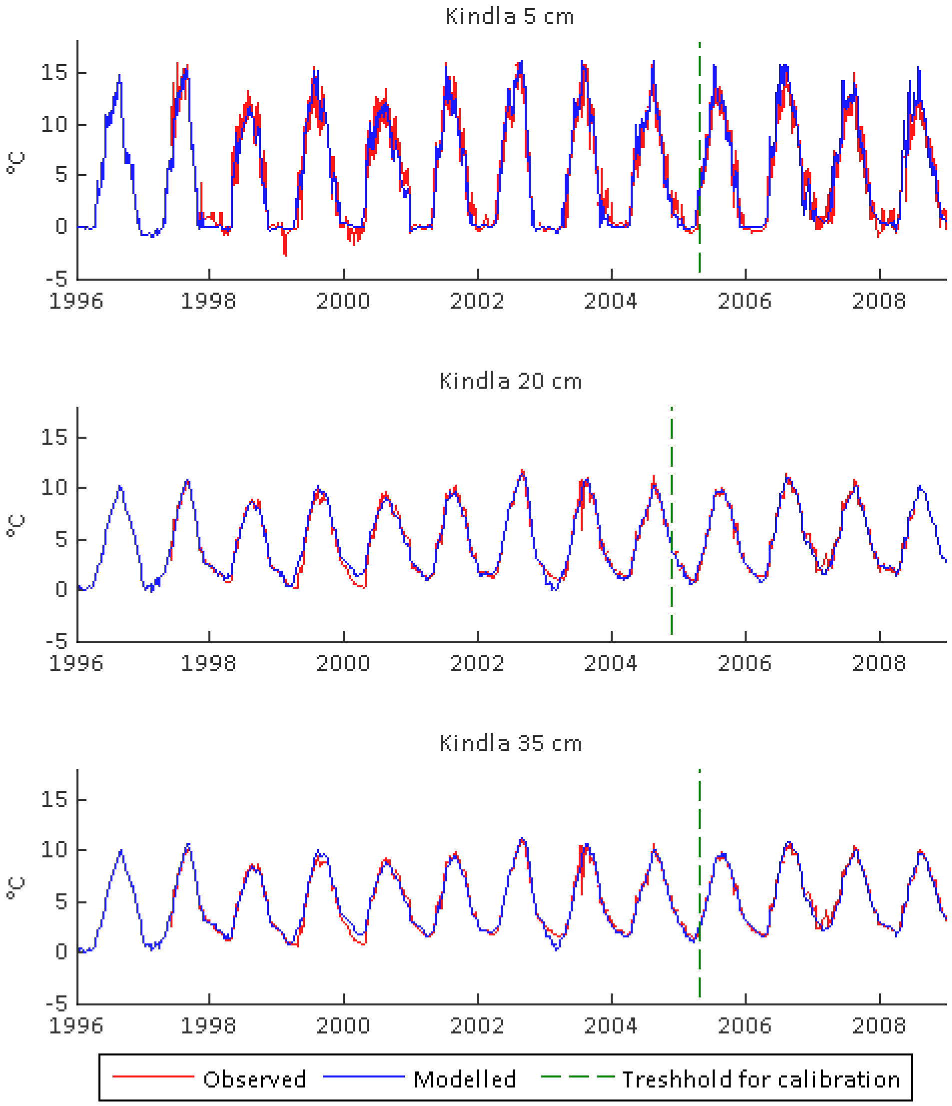

Figure 8 Simulated and observed soil temperature during 1996-2008 for Kindla

The average performance of the model simulations at Gammtratten was satisfying for both the calibration and the validation period (Figure 9). Although the overall simulations were very good, the model overestimated or underestimated the soil temperature at some points, which were reflected in the overall goodness of fits in the catchment (Table A7). The goodness of fit during the validation period was the lowest in this study. The NS values ranged from 0.966 to 0.976 for the calibration period and from 0.931 (lowest value recorded) to 0.951 for the validation period (Table A7). For the purpose of this thesis, simulated values at Gammtratten had problems duplicating some of the winter temperatures, which were not quite captured by the model (Figure 9). This makes Gammtratten the only site in the study where the model poorly estimated winter soil temperatures, especially during the soil's cooling and heating (Figure 9). The insulating effect due to snow cover is clearly visible (as the winter temperature flattens out) during the winter moths (Figure 9).

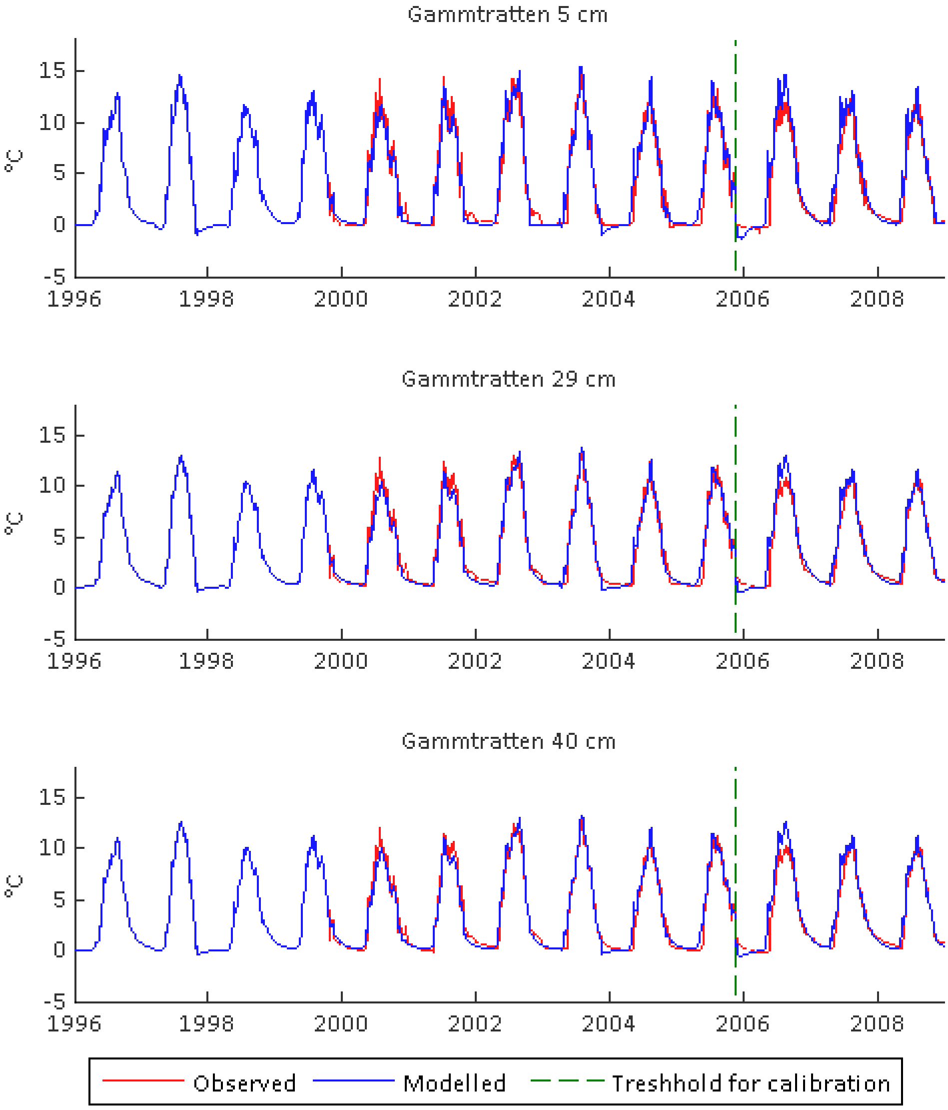

Figure 9 Simulated and observed soil temperature during 1996-2008 for Gammtratten

3.2.2 Snow model

The snow cover for each study site was simulated using literature values as model parameters. Due to the absence of observed data for site specific calibration of the snow model, the snow depth simulations should be threatened with caution. The least number of days with snow cover were simulated at Gårdsjön (Table 6), while Gammtratten had the most number of days with snow cover (Table 6), which were in line the expectations. Average snow depth was quite similar at Aneboda and Gårdsjön for the calibration/validation period, whilst Kindla and Gammtratten had significantly more snow during the same period. Simulated snow depths at Kindla were on yearly average deeper than Gammtratten (Table 6). This observation was not surprising given the fact that Kindla has more precipitation (Table 1), though Gammtratten is further north (Figure 1).

Table 6 Simulated snow cover during 1996-2008 for the IM study sites and reported number of days with snow cover during 1961-1990

	Aneboda	Gårdsjön	Kindla	Gammtratten
Snow cover				
Year	Days	Days	Days	Days
1996	152	132	152	195
1997	97	78	153	212
1998	127	88	176	199
1999	102	79	158	185
2000	54	22	132	184
2001	106	31	171	197
2002	59	92	182	201
2003	71	95	151	180
2004	94	96	150	173
2005	89	94	145	164
2006	102	122	142	195
2007	55	64	139	176
2008	62	29	165	185
Mean	90	78.6	155.1	188.2
Observed*	110	50	150	175
Snow depth (1996-2008)				
Mean, Nov-Mar (mm)	46.7	46.2	168.2	139.2
Max. value (mm)/year	526/1996	560/2006	577/1997	501/1996

* Long –term average climatic data 1961-1990 (Löfgren et al., 2011).

3.2.3 Uncertainty analysis

The distribution mapping and the cumulative distribution frequency plots could not reveal much information on specific parameter values due to parameter correlations (Refsgaard et al., 2007). Quantifying comparative parameter distributions results (between sites and depths) from the Monte Carlo analysis was generally difficult because of the wide spatial heterogeneity of parameter distributions. The uncertainty analysis of the model revealed that the model has equifinality (Beven, 2006). This means that there is no single best model parameter setting and that many model state descriptions can generate equally good calibration outputs. For these reasons it was hard to know the optimum parameter values from the model calibration that best represent the present day conditions in the soil. Additionally, it was hard making catchment comparisons due to the fact that soil temperatures were simulated at different depths for the different sites. However, some results were able to be distinguished. For example, K_T was clearly the most sensitive parameter (Figure 10a), while $C_{S,ICE}$ was highly insensitive (Figure 10b). This result was consistent in all sites and at all depths.

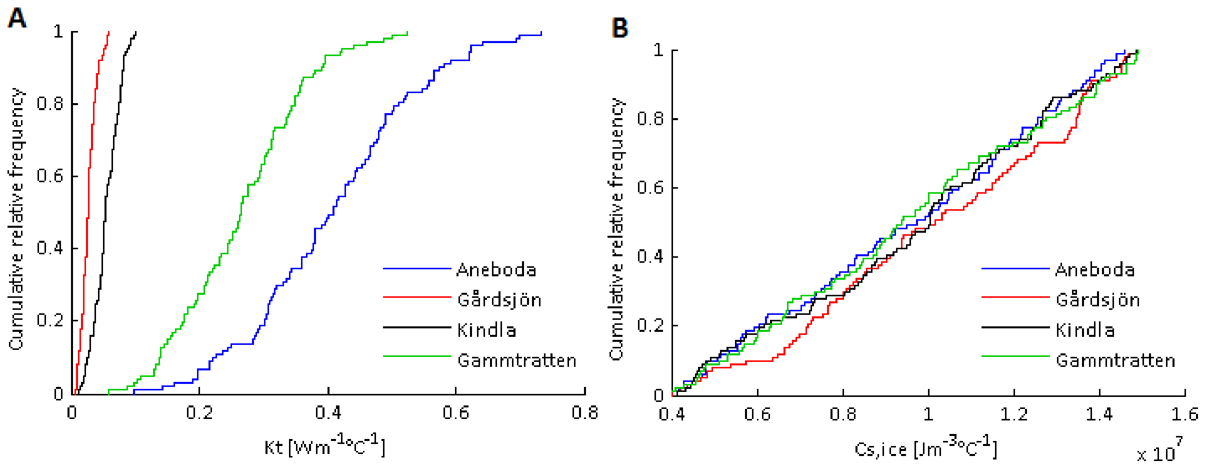

Figure 10a and 10b Cumulative relative distributions for K_T (plot a) and $C_{S,ICE}$ (plot b) from the Monte Carlo simulations middle soil layers across the four IM sites.

3.3 ENSEMBLE PROJECTIONS OF SNOW AND SOIL TEMPERATURE DYNAMICS

Future projections (2061-2090) indicated higher annual soil- and air temperatures than the test period (1996-2008). This result was consistent for all sites and for all ensembles projections. Air temperature was noted to be changing more than soil temperature on annual basis, with the exception of Aneboda. The future projections revealed somewhat different seasonal behavior between sites. At all sites, the differences in soil temperature between the calculated maximum monthly value and monthly average for the test run (1996-2008) were highest in the summer months (Figures 12, 14, 16 and 18). The median ensemble outputs showed wide differences in future conditions between sites. For the two southernmost sites, projected winter (especially January-March) soil temperature was clearly higher than during 1996-2008. At Kindla, winter soil temperatures were quite similar to that of the test period, whilst Gammtratten in the north had lower winter soil temperatures.

3.3.1 Aneboda

Future ensemble projections in Aneboda showed that annual air temperature could be changing almost to the same degree as soil temperature (Figure 11). The ensemble median projection showed about 2.3 °C and 2.4 °C rise in annual air- and soil temperatures respectively than the test period. The future ensemble projections covered a wider range for air temperature than for soil temperature (Table B1). Based on range of RCM ensembles projections considered in this study, annual soil temperature is likely to be somewhere between 7.11 and 8.62 °C by 2061-2090.

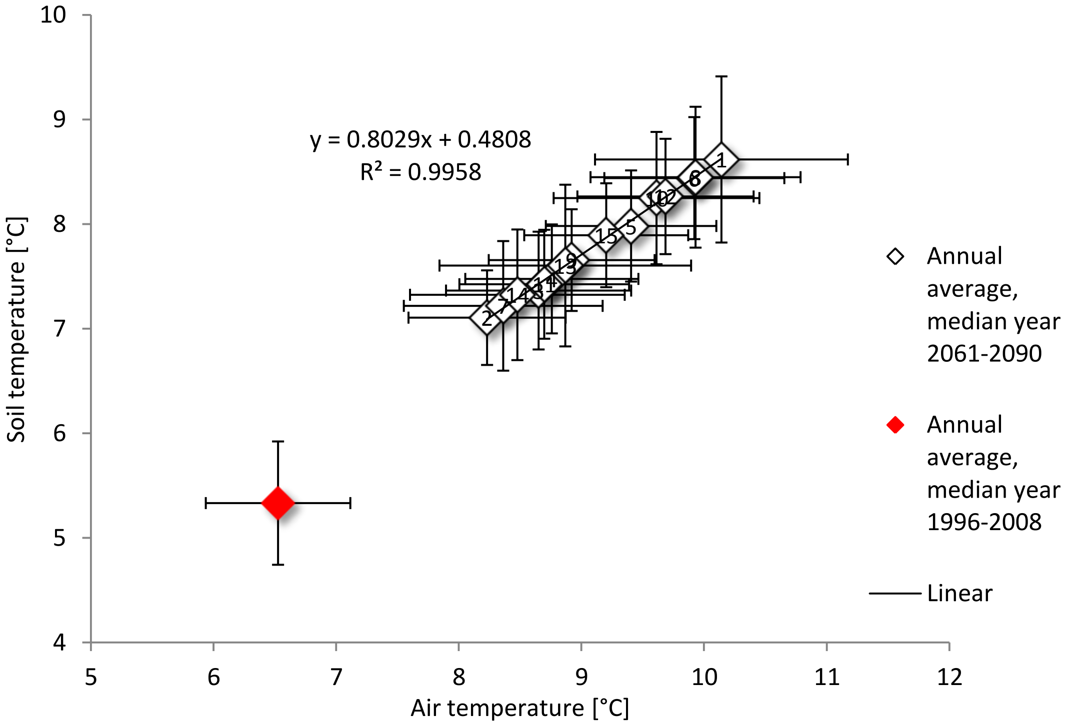

Figure 11 Simulated annual average air- and soil temperature for the ensembles predictions (*diamonds*, label 1-15 denote each RCM in Table 2), using ensemble median for Aneboda middle soil layer versus annual average air- and soil temperature for the calibration/validation period, median year (*red square*). *Error bars* represent corresponding annual standard deviations

The projected climate at Aneboda (2061-2090) could have the most pronounced effects on soil temperature in the summer (Figure 12). Additionally, winter soil temperatures were also clearly higher for the future projections than that of the test period (1996-2008), especially in March where 2.61 °C difference was recorded (Table B5). Even though the projected precipitations were higher in the winter months (Figure 4), the relatively small amount of precipitation in addition to higher winter air temperatures (Figure 5) had large impacts on snow accumulation in Aneboda. The simulated snow depth decreased for the future condition as depicted by the ensemble median and minimum. The results therefore showed that snow could disappear almost completely in the catchment in the future (Figure 12).

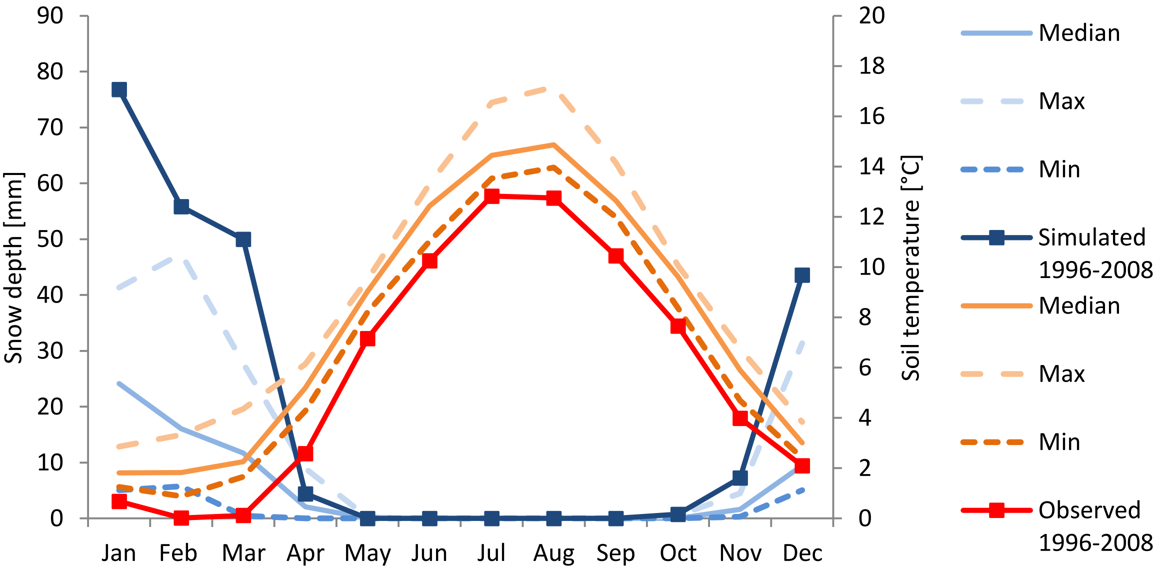

Figure 12 Simulated monthly average soil temperatures 2061-2090, ensembles median (*solid orange line*), maximum (*dashed orange line*) and minimum (*dotted orange line*) outputs. Observed monthly average soil temperature 1996-2008 (*red solid-dotted line*). The plot also shows simulated monthly average snow depth 2061-2090, ensembles median (*solid blue line*), maximum (*dashed blue line*) and minimum (*dotted blue line*) outputs. Simulated monthly average snow depth 1996-2008 (*blue solid-dotted line*). All simulations represent Aneboda middle layer

3.3.2 Gårdsjön

At Gårdsjön on the west coast, annual air- and soil temperature were projected to be higher in the future (2061-2090) than for the test period (1996-2008) (Figure 13). The ensemble median of annual soil temperature was 1.44 °C higher than for the test period (1996-2008). This is in contrast to the 2.62 °C increase in annual air temperature during the same period (Table B2). This is an indication that air temperature could be changing more rapidly than soil temperature in Gårdsjön. On annual scale, the ensemble RCMs range of projected change made the estimation of future soil temperature at Gårdsjön somewhere between 8.22 and 9.82 °C (Table B2).

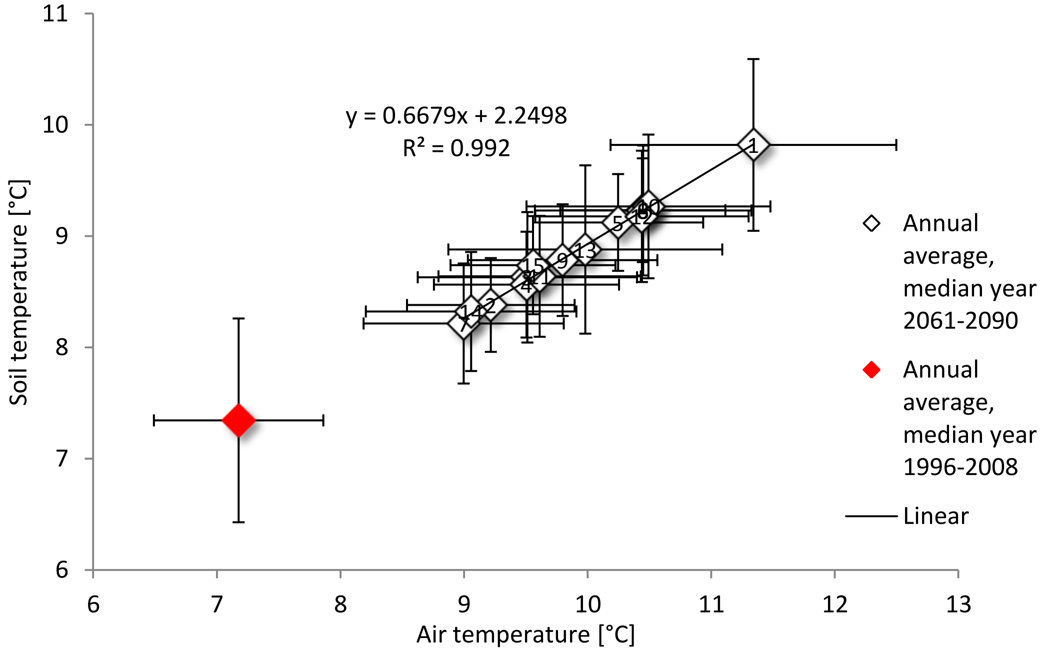

Figure 13 Simulated annual average air- and soil temperature for the ensembles predictions (*diamonds*, labeled 1-15), using ensemble median for Gårdsjön middle soil layer versus annual average air- and soil temperature for the calibration/validation period, median year (*red square*). *Error bars* represent corresponding annual standard deviations

On seasonal scale, the range of projected future variations at Gårdsjön revealed that late summer and winter temperatures could change the most from that of the test period (1996-2008). The simulated ensemble median of monthly soil temperature deviated the most from that of the test period in March (2.29 °C degrees higher for the future run), but summer temperatures was also projected to change quite considerable (Table B6). The projected increase in precipitation during winter months (Figure 4) was not converted into more snow at Gårdsjön due to increase in winter air temperatures (Figure 5). Therefore simulated snow depth decreased for the future run (Table B10).

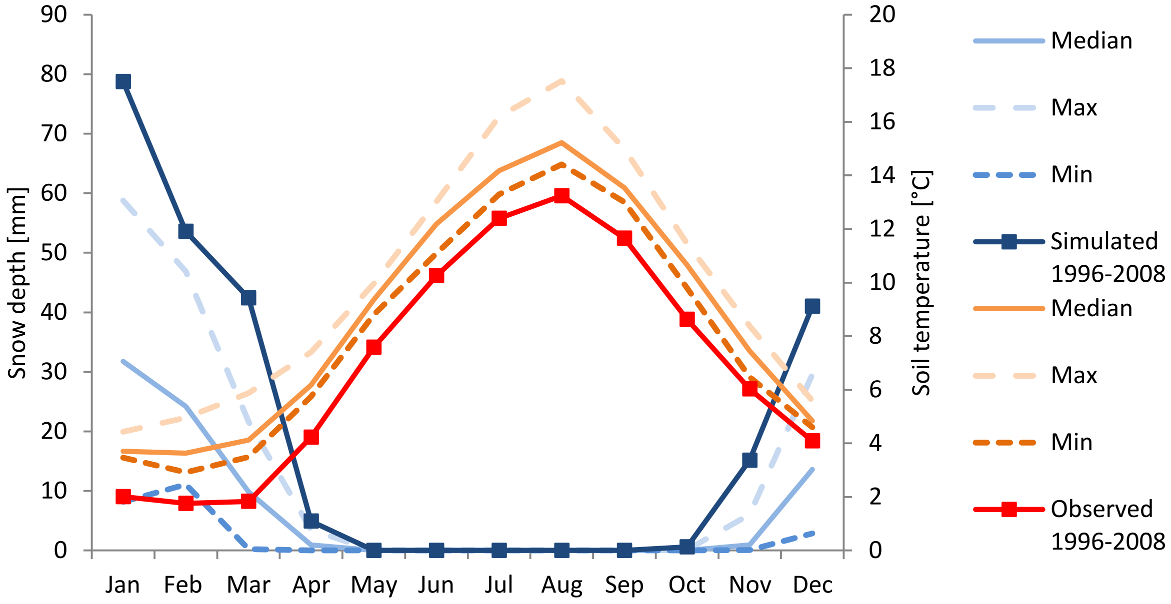

Figure 14 Simulated monthly average soil temperatures 2061-2090, ensembles median (*solid orange line*), maximum (*dashed orange line*), minimum (*dotted orange line*) outputs. Observed monthly average soil temperature 1996-2008 (*red solid-dotted line*). Simulated monthly average snow depth 2061-2090, ensembles median (*solid blue line*), maximum (*dashed blue line*), minimum (*dotted blue line*) outputs. Simulated monthly average snow depth 1996-2008 (*blue solid-dotted line*). Gårdsjön middle soil layer

3.3.3 Kindla

Annual air temperature was also projected to be higher than annual soil temperature by all RCMs (Figure 15) at Kindla. The median future ensemble projection showed that the annual soil temperature could be 1.3 °C higher than for the test period. For the same period, the median ensemble for annual air temperature was projected to be 2.5 °C higher (Table B3). The range of projected soil temperatures was 1.0 °C (scenario 1 and 7) and 1.89 °C for air temperature (scenarios 1 and 7). The projected soil temperature at Kindla could likely be somewhere between 5.81 and 6.81 °C in the future (Table B3).

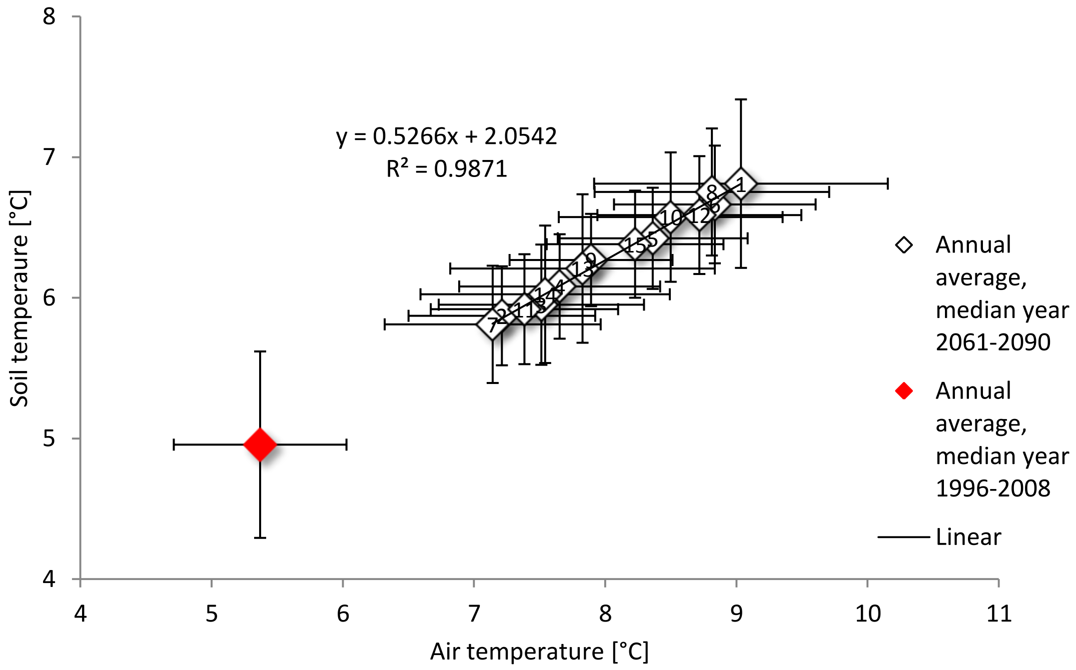

Figure 15 Simulated annual average air- and soil temperature for the ensembles predictions (*diamonds*, labeled 1-15) using median year for Kindla middle layer relative to average air- and soil temperature for the calibration/validation period using median year (*red square*). *Error bars* represent corresponding annual standard deviations.

At Kindla, the magnitude of the difference in projected soil temperatures between test (1996-2008) and future period (2061-2090) was not as high as for Gårdsjön and Aneboda. However, all RCMs showed possible higher temperatures for the future than for the test period. This is particularly noted in April and August/September as depicted by the ensemble maximum (Figure 16). The ensemble median projection showed that soil temperatures could rise by about 1.5 °C in the future run for most of the year, except for Dec-Feb were temperatures will only be about 0.5 °C higher than for the test period (Table B7). Snow cover could be substantially reduced at Kindla in the future (Figure 16).

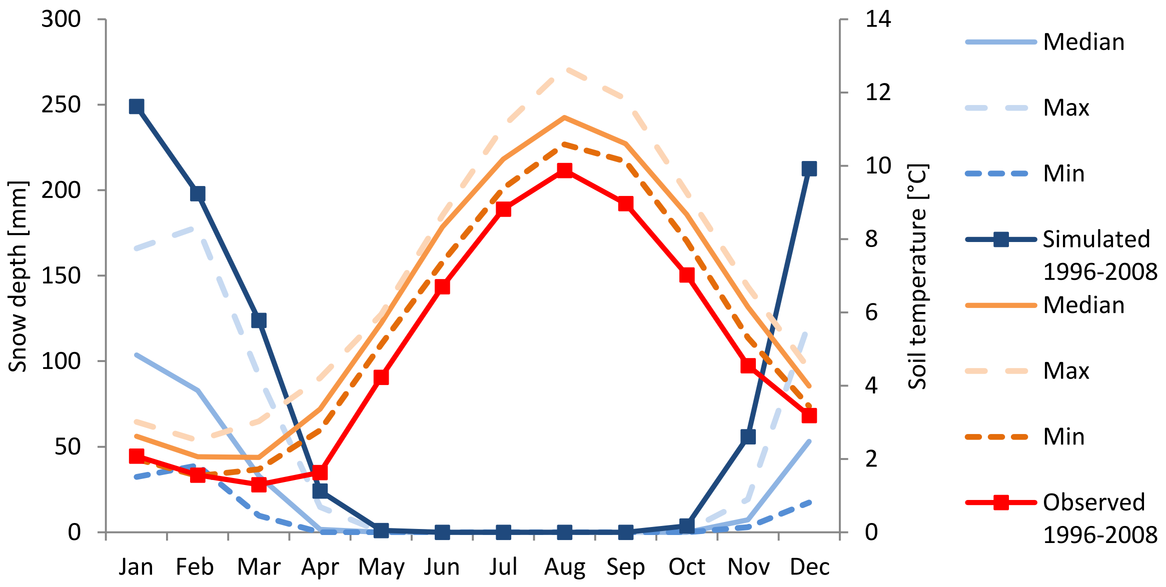

Figure 16 Simulated monthly average soil temperatures 2061-2090, ensembles median (*solid orange line*), maximum (*dashed orange line*), minimum (*dotted orange line*) outputs. Observed monthly average soil temperature 1996-2008 (*red solid-dotted line*). Simulated monthly average snow depth 2061-2090, ensembles median (*solid blue line*), maximum (*dashed blue line*) and minimum (*dotted blue line*) outputs. Simulated monthly average snow depth 1996-2008 (*blue solid-dotted line*). Kindla middle soil layer

3.3.4 Gammtratten

According to the future projections at Gammtratten, annual air- and soil temperature would also be higher in the future than the test period (1996-2008) (Figure 17). Ensemble median projections also showed that air temperature could change more than soil temperature (3°C and 1.40 °C respectively) in the future. The ensembles soil temperature projections covered a 1.26 °C range, making the annual soil temperature likely be to somewhere between 4.80 and 6.06 °C in the future (Table B4).

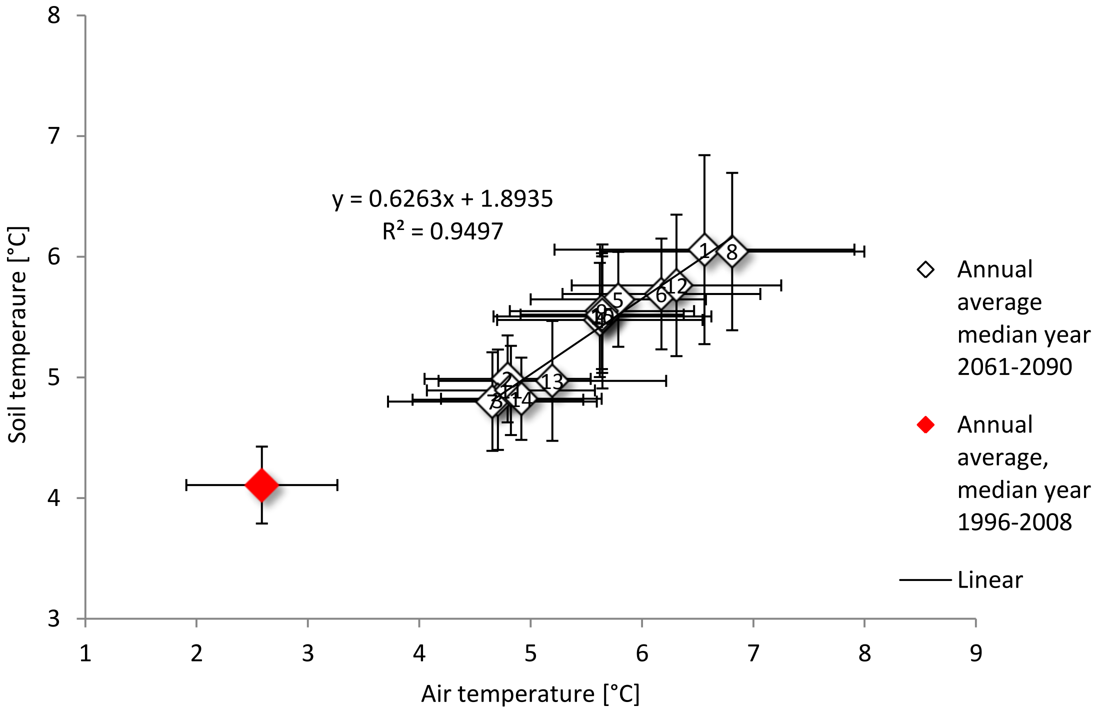

Figure 17 Simulated annual average air- and soil temperature for the ensembles predictions (*diamonds*, labeled 1-15), using ensemble median for Gammtratten middle soil layer versus annual average air- and soil temperature for the calibration/validation period, median year (*red square*). *Error bars* represent corresponding annual standard deviations

On a seasonal scale, Gammtratten differs from the other sites in the sense that the future winter soil temperatures could get even colder than the test period (Figure 18). For example, ensemble median projections showed that February could be 0.4 °C lower than the test period (Table B8). However, the spring and summer could get a lot warmer in the future. Snow might not completely disappear to the same degree as for the other study sites (Figure 18). Ensemble median and maximum projected more snow depths than the simulated values for the test period (Figure 18) in most winter months (especially during the later winter months). However, when each RCM ensemble members were examined more carefully, some RCMs (such as ETHC) projected lesser snow and colder soil temperatures during the winter (Figure 19). This result could be related to soil heat loss due to less insulating snow. However, this conclusion could not be generalized in the catchment since other RCMs (e.g. SMHI_BCM) also projected colder soil temperatures but with more snow than the test period simulations (Figure 19). Furthermore, these low soil temperatures were not a result of lower air temperature since both ETHC and SMHI_BCM projected an increase in winter air temperatures in the future.

As depicted in the ensemble median, Gammtratten is also the only study site that that showed the possibility of having more snow in the future. Both precipitation and air temperature increased for the future conditions in other catchments (Figures 4 and 5), Gammtratten was however the only study site with a possibility of more snow as increases in temperature changes were compensated for by more precipitation.

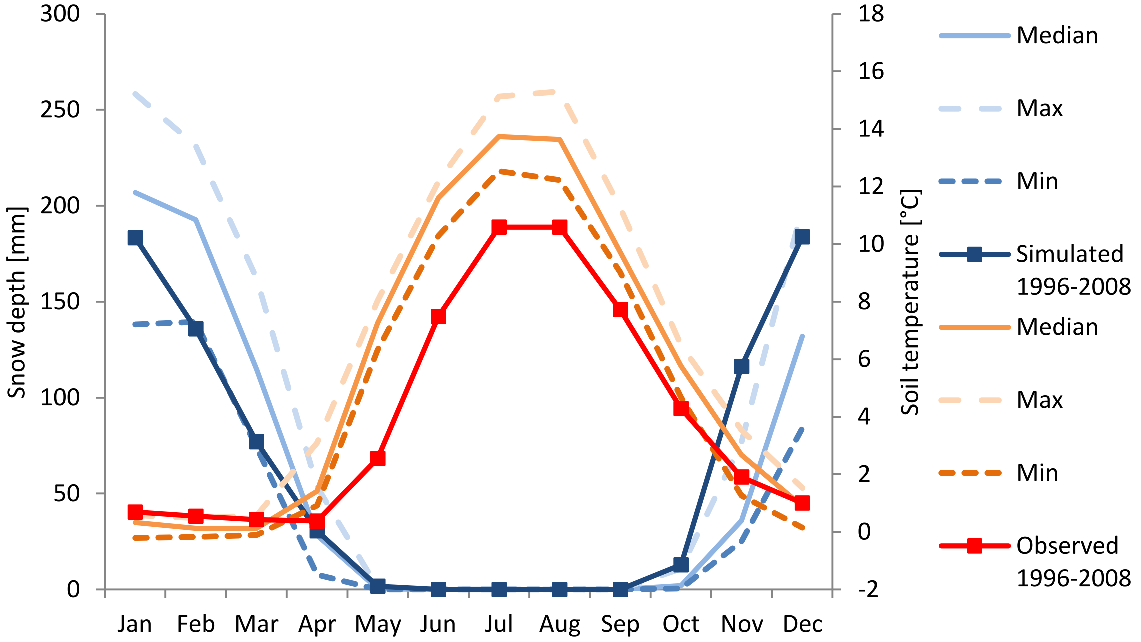

Figure 18 Simulated monthly average soil temperatures 2061-2090, ensembles median (*solid orange line*), maximum (*dashed orange line*), minimum (*dotted orange line*) outputs. Observed monthly average soil temperature 1996-2008 (*red solid-dotted line*). Simulated monthly average snow depth 2061-2090, ensembles median (*solid blue line*), maximum (*dashed blue line*), minimum (*dotted blue line*) outputs. Simulated monthly average snow depth 1996-2008 (*blue solid-dotted line*). Gammtratten middle soil layer

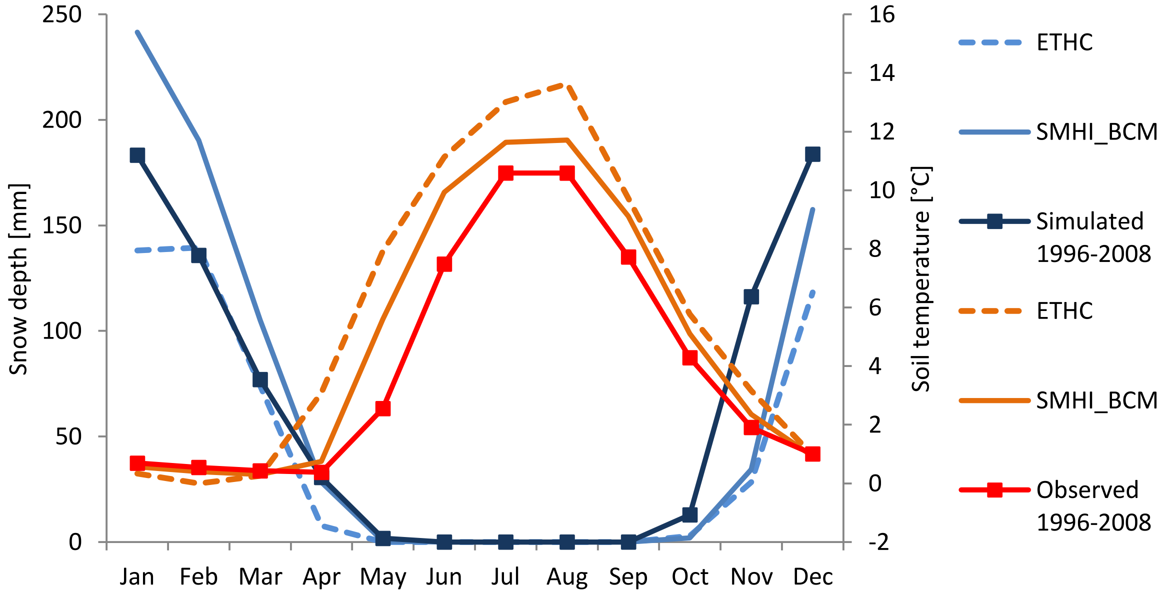

Figure 19 Simulated monthly average snow depth (*blue lines*) and soil temperature (*red lines*) for Gammtratten middle layer, SMHI_BCM (*solid lines*) and ETHC (*dotted lines*) projections

3.3.5 Climate gradients

Comparing the future and present day air- and soil temperatures for the four study sites highlights the magnitude of the effect of climate change on soil temperature across the south-north gradient of Sweden. For example, future condition in Gammtratten by the end of the century could shift toward present day air –and soil temperatures in Kindla or Aneboda (Figure 20).

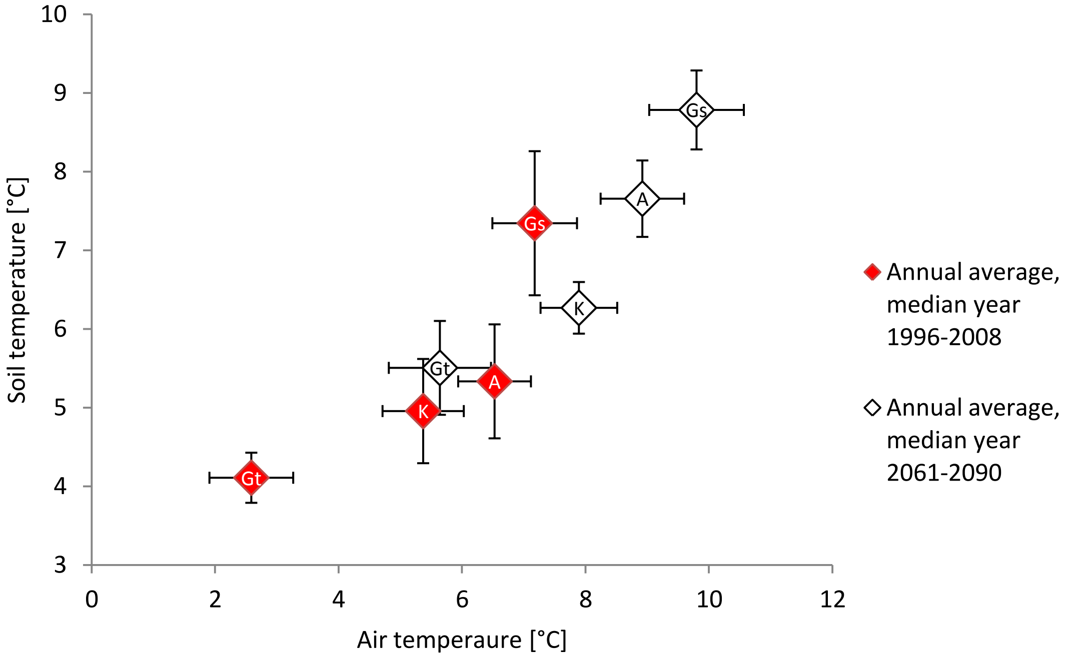

Figure 20 Projected annual soil temperature using the RCM ensemble median (*white diamonds*) for Aneboda (*A*), Gårdsjön (*Gs*), Kindla (*K*) and Gammtratten (*Gt*) versus observed median soil temperatures for the test period (*red diamonds*). *Error bars* represent corresponding annual standard deviations

4 DISCUSSION

4.1 PRESENT AND FUTURE CLIMATE DATA

The analyses of the climate ensemble data used for driving the snow-soil temperature model in this thesis was based on the ensemble median of the different RCM projections. The overall outcome projected an increase in total annual precipitation and annual mean temperature. In terms of seasonal changes, precipitation and temperature were projected to increase for most months of the year, although the change will likely be more pronounced during winter. Considering temperature changes, the period with temperatures below 0 °C was projected to shorten considerably in the Northern catchments (Kindla and Gammtratten) and to disappear completely in the Southern catchments (Aneboda and Gårdsjön). These higher temperatures could have major influence on the accumulation/melting of snow and soil temperatures. Possible other effects, not investigated in this thesis, are changes in runoff regimes, ecosystem productivity, changes in water quality etc. Other studies have pointed out the effects of climate change on ecosystems in Sweden, including effects on the distribution of tree species and community composition (Koca et al., 2006).

4.2 MODEL CALIBRATION AND VALIDATION

The soil temperature simulations were able to capture the behaviors of observed soil temperature to a very satisfying degree. The results from the calibrations of the soil temperature models were well beyond the expectation. The lowest recorded NS value for the validation of the models was 0.931 which is considered to be very high. The calibrated model also seems to capture the seasonal variations in soil temperature in a satisfying way. Both the high summer temperatures and the low winter temperatures were generally reached by the simulations.

The model underestimated some winter temperatures, particularly when soils cool down during the autumns and heat up during spring. However, this pattern was only recorded as more frequently occurring in Gammtratten. Gammtratten was also the study site where the influence of snow cover was the most visible. Similar observations from soil temperature modeling in Finland were also made by Rankinen et al. (2004a), suggesting the need for an improved model-setup where heat-flow could be allowed to influence the soil layer of consideration from below. Whether these issues still remain after the implementation of the complementary heat flow equation suggested in this thesis is debatable. It is uncertain whether the observed difficulties in simulating winter soil temperatures in Gammtratten should be regarded as a systematic model-setup shortcoming (e.g. poor sensitivity to snow cover or poor heat flow estimations) or as a model calibration issue.

However, the overall simulations of winter soil temperatures were satisfactory in all study sites considered in this thesis. This conclusion implies that the extended soil temperature model proposed in this thesis indeed offered improved soil temperature modeling; a major result in this study. Soil temperature is very important in predicting other biochemical processes in the soil, and can be implemented in other environmental source assessment models, such as INCA-N (Whitehead et al., 1998), INCA-P (Wade et al., 2002) or INCA-C (Futter et al., 2007). For example, dissolved organic carbon has been shown to be strongly correlated to soil temperature (Winterdahl et al., 2011). The carbon response to climate change effects is however very complex, suggesting the need for proper soil temperature modeling (Brooks et al., 2011; Futter et al, 2011).

The simulations of snow cover, in the combined snow-soil temperature model, have not been verified by calibration on observed data and are deemed as uncertain. Site specific calibration is of course a big asset but not always possible. Given the catchment differences in precipitation and air temperature, site specific calibration of snow depth parameters may have enabled better tuning of thresholds T_{UP}, T_{LOW} and correlation of solid precipitation parameter, and would have enabled validated snow fall conversion at each site. In comparison to observed data (1961-1990) the number of days with snow cover is assessed to be quite accurate, at all sites, there is however a uncertainty concerning the snow depth. This uncertainty can be attributed to the fact that model estimates snow depth by first calculating snow as water equivalent, and then converts it into snow depth by division with the snow density. The snow cover gets more compact as the snow undergoes aging, through an aging factor. Wrongfully set aging factor could have led to too high or too low snow depth simulations.

General uncertainty analysis of the soil temperature model was performed. The uncertainty analyses revealed that the model parameters showed equifinality. This means that there are several parameter settings which would result in equally good model outputs. This fact was thought to be a result of the strong correlation between parameters. Due to the equifinality of the parameters, it was difficult to determine if the calibrated parameters actually represented the conditions in the soil and their sensitivity was very difficult to evaluate. The parameter $C_{S,ICE}$ appeared to be highly insensitive. This observation is not surprising since $C_{S,ICE}$ only comes into play when the soil temperature drops below zero. Even if the parameter was changed during model calibration, it would not affect the NS value so much since it only affects the NS value on the rare occasions of freezing soil temperatures. This argument also holds for parameter f_S, which only affects NS when there is snow. Calibrating only for the winter would reveal more about the true sensitivity of the mentioned parameters. However, the main purpose of the model to simulate the soil temperature at different depths was achieved.

4.3 FUTURE PROJECTIONS

Simulations of future indicated higher soil- and air temperatures relative to the test period. This result was general in all IM sites and in all RCM projections. Air temperature was projected to increase throughout the study sites and the changes would be more than soil temperature on annual basis. The ensembles median projections showed that annual soil temperatures could increase relative to the test period by 1.31 – 2.33 °C. Air temperatures were projected to increase by 2.39 – 3.06 °C. Using Aneboda and Gammtratten as surrogates for southern and northern Sweden, the results indicated that soil temperature would differ significantly from air temperature especially in the northern parts of Sweden. Earlier study on soil temperature in Canada has also shown that soil temperature differs from air temperature (Zhang et al., 2005). The authors attributed the difference in air-soil temperature to the effect of more pronounced snow cover insulation in high latitude catchments (Zhang et al., 2005). Comparing Gårdsjön catchment in the south (with even warmer winter air temperature than Aneboda) with Gammtratten catchment in the north showed similar patterns in the future projections presented here, even though not as distinct.

Seasonal variations in soil temperatures suggested that winter soil temperatures could be higher in the future for the southern catchments, Aneboda, Gårdsjön and Kindla. In Gammtratten catchment, winter soil temperatures could become lower in the future. Other studies have suggested possibility of lower soil temperatures in boreal regions in the future (Stieglitz et al., 2003, Brown et al., 2011). Lower winter soil temperatures could have huge effects on ecosystem carbon and nutrient fluxes. Recorded effects are for example nutrient losses due to increased fine root mortality (Fitzhugh et al., 2001) and decreasing decomposing rates as a result of less microbial activity (Kreyling et al., 2013). The effect of lower winter soil temperatures were recorded at Gammtratten but the conclusion is not unambiguous as whether it would result from less snow cover. This is because some RCMs projected colder soil temperatures as a result of snow loss while others projected colder soil temperature but with more snow. Ensembles median even projected increase winter average snow cover.

Since most climate models predict higher winter air temperatures in northern regions, soil frost might increase as a result of the counter effect of less insulating snow. There is however the possibility of more snow if the warmer air temperatures is compensated for by more precipitation. Seasonal redistribution of snow cover would therefore be of uttermost importance in this region. Since more snow at Gammtratten was generally projected towards the end of the winter, the effect of lower soil temperatures could be attributed to the effect of snow cover insulating the soil from warming during late winter and spring. These observations showed that projecting the effect of climate change on soil temperature in snow dominated regions is very complex and large uncertainty still exists. General assumptions of winter soil temperature dynamics based on future changes in air temperature alone should be made with caution.

Unfortunately for the reliability of the future predictions at Gammtratten, driving climate data had to be substituted with bias-corrected RCM data from a neighboring catchment (Krycklan) for the future run. Given the fact that Krycklan had more precipitation during the control period (used for bias-correcting the RCMs) then Gammtratten; it is possible that also the future prediction overestimated the amount of precipitation at Gammtratten. Which in that case possible would have resulted in less snow then was generated in this study. What consequences that would have had on soil temperature cannot be assessed due to the complex relationship between soil and air temperature and the counter effects of snow cover. However, due climatic similarities of the two sites and the general uncertainties in future predictions, it cannot be ruled out that the driving projections used in this study actually were a good representation of future conditions at Gammtratten.

On the annual scale, soil temperatures could increase in all study sites. For example, future condition in Gammtratten could be similar to present day (test period) climate and soil temperature in Aneboda. This might have consequences on the biomes, growing season amidst others in this northern catchment. For example, higher temperatures could increase the plant-derived carbon to the soil due to longer growing season for plants (Davidson and Janssens, 2006). Increasing air temperatures on a global scale may result in positive feedback to climate change that would subsequently reinforce the global warming due to higher decomposing rates in soil increasing, terrestrial CO_2 emission to the atmosphere (Davidson and Janssens, 2006). The uncertainty on the effect of a future climate on soil temperature and snow dynamics is still large.

4.4 RECOMMENDATIONS FOR FUTURE STUDIES

To further test the internal working process of the model presented in this thesis, future applications to other catchments are required In order to reduce the effect of equifinality on the model parameters, further studies should apply a fixed soil property value for either the soil's thermal conductivity (K_T) or the soil's specific heat capacity (C_S). These values should be based on field measurements and/or estimated based on soil type. Since C_S was regarded as the less sensitive parameter in this study, it would be more appropriate to use a fixed value in the future. This would make it easier to evaluate the sensitivity and distributions of other parameters.

Soil temperature measurements should be collected from the same depth in the soil profiles to make the work comparable to study sites. By comparing the same depths, it would also be easier to know whether parameter behaviors are due to soil type properties or the effect of that the soil properties are changing with depth in the profile.

For optimizing the model in simulating winter temperatures, future works should consider using only winter soil/air temperatures data for model calibration. This would affect the goodness of fit evaluation criterion if the winter temperatures are simulated wrongly. Additionally, it would be easier to verify “winter parameters” (f_S and $C_{C,ICE}$) distributions and sensitivities.

The need to substitute the future climate data for the most northern study site (Gammtratten) with climate data from a neighboring catchment was a shortcoming in this study. For future climate change impact studies on the Swedish IM sites, it is recommended that that bias-corrected climate data for Gammtratten is used.

5 CONCLUSION

- The proposed soil temperature model used in this study was adequate enough to simulate soil temperature, with the influence of snow cover at different depths in the soil profile and at different study sites in Sweden.
- It is uncertain whether the model offered an improvement of the existing model
- Air temperature and soil temperatures are likely going to be higher in the future. Future air temperature could increase by about 2.39 – 3.06 ^{o}C and soil temperature by 1.31 – 2.33 ^{o}C relative to the present day conditions on annual scale. Changes in soil temperature could be higher in south than in the north.
- Snow depth is likely to decrease significantly in the south during the winters, while it might even be increase in the north.
- In this study both higher and lower winter soil temperatures were recorded but there were no clear signals whether to attribute the observations to snow loss.

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APPENDIX A

PRESENT AND FUTURE CLIMATE DATA

Table A 1 Monthly precipitation (mm), simulated ensembles median and observed monthly precipitation 1996-2008 for the four IM study sites.

	Aneboda		**Gårdsjön**		**Kindla**		**Gammtratten**	
Month	**Sim.**	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**Obs.**
Jan.	79	54	153	112	109	62	58	36
Feb	49	41	85	75	66	50	44	32
Mar.	57	41	81	66	53	42	46	22
Apr.	69	49	86	73	46	43	39	31
May	82	72	75	74	80	68	51	39
Jun.	75	70	114	108	89	85	63	58
Jul.	127	107	82	80	126	91	98	90
Aug.	87	87	92	98	95	93	94	86
Sep.	60	58	101	87	57	61	72	49
Oct.	93	88	137	126	134	92	77	51
Nov.	75	60	134	106	126	85	70	48
Dec.	95	68	154	107	86	82	60	38
Winter (Nov.-Mar.) average	71	53	121	93	88	64	56	35

Table A 2 Monthly average air temperature (°C), simulated ensembles median and observed monthly average air temperature 1996-2008 for the four IM study sites.

	Aneboda		**Gårdsjön**		**Kindla**		**Gammtratten**	
Month	**Sim.**	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**Obs.**	**Sim.**	**Obs.**
Jan.	1.5	-1.8	1.8	-1.0	-0.6	-3.5	-4.9	-7.6
Feb	1.5	-1.7	2.2	-0.8	-0.2	-3.7	-4.5	-8.0
Mar.	3.0	-0.1	3.7	0.6	1.8	-1.3	-1.1	-4.6
Apr.	7.9	5.3	8.8	5.8	7.0	3.9	4.5	1.3
May	12.2	10.2	13.0	10.4	11.6	9.0	11.0	6.5
Jun.	16.2	14.0	16.8	14.2	16.0	13.3	15.3	12.1
Jul.	17.8	15.9	18.6	16.4	17.8	15.7	17.1	14.8
Aug.	17.8	15.4	19.5	16.2	17.7	14.9	16.1	13.2
Sep.	13.5	11.3	14.4	12.1	12.7	10.3	10.3	8.2
Oct.	9.8	6.6	10.4	7.0	7.8	4.9	5.5	2.2
Nov.	5.2	2.2	5.4	2.7	3.4	0.5	0.4	-3.6
Dec.	2.2	-0.6	2.6	0.1	0.4	-2.6	-3.7	-6.8
Winter (Nov.-Mar.) average	2.7	-0.4	3.1	0.3	1.0	-2.1	-2.8	-6.1

Table A 3 Calibrated parameters for the soil temperature models

Site\Parameter	C_S (10^6)	K_T	$C_{S,ICE}$ (10^6)	f_S	T_{LOW}	$K_{T,LOW}$	$C_{S,LOW,}$ (10^6)
Aneboda							
10 cm	2.65	0.02	4.10	-0.14	2.01	0.74	2.72
32 cm	2.89	0.48	7.90	-0.24	1.91	0.45	2.53
58 cm	2.81	0.37	0.66	-0.30	5.35	0.12	2.88
Gårdsjön							
0 cm	2.36	0.00	7.26	-1.24	4.48	0.70	2.14
10 cm	1.45	0.01	14.66	-0.41	6.39	0.89	2.56
25 cm	1.96	0.06	9.49	-0.45	6.38	0.13	0.73
Kindla							
5 cm	1.90	0.01	8.24	-1.65	0.17	0.95	2.23
20 cm	2.55	0.04	8.63	-0.35	3.49	0.39	2.03
35 cm	0.71	0.03	10.20	-0.49	3.31	0.33	3.28
Gammtratten							
5 cm	3.18	0.02	6.82	-7.14	0.01	0.43	0.96
29 cm	1.68	0.17	5.77	-9.89	0.18	0.47	2.34
40 cm	2.84	0.54	5.69	-9.66	0.05	0.23	1.48

MODEL CALIBRATION AND VALIDATION RESULTS

Table A 4 Calibration and validation results for the simulated soil temperatures at Aneboda for the three different soil profile depths

Parameter\Site	Aneboda 10 cm	Aneboda 32 cm	Aneboda 58 cm
Calibration period			
N	2773	2801	2047
NS value	0.958	0.963	0.972
Observed mean	4.97	5.42	5.63
Simulated mean	5.30	5.71	5.90
Observed max. value	14.70	15.60	12.20
Simulated max. value	13.76	15.47	12.28
Observed min. value	-4.26	-3.81	0.10
Simulated min. value	-1.95	-2.37	-0.15
Validation period			

N	1388	1403	1025
NS value	0.974	0.963	0.973
R^2 value	0.978	0.969	0.980
RSME value	0.648	0.880	0.555
Observed mean	5.27	5.59	5.61
Simulated mean	5.76	6.20	6.44
Observed max. value	13.30	15.00	12.10
Simulated max. value	14.01	16.03	12.55
Observed min. value	-1.10	-1.65	0.68
Simulated min. value	-1.72	-1.86	-0.38

Table A 5 Calibration and validation results for the simulated soil temperatures at Gårdsjön for the three different soil profile depths

Parameter\Site	**Gårdsjön 0 cm**	**Gårdsjön 10 cm**	**Gårdsjön 25 cm**
Calibration period			
N	1638	1638	1638
NS value	0.972	0.980	0.988
Observed mean	6.96	7.12	6.98
Simulated mean	6.38	6.64	6.60
Observed max. value	15.30	15.32	13.65
Simulated max. value	16.76	16.02	13.75
Observed min. value	-1.01	-0.66	1.17
Simulated min. value	-0.48	-0.29	0.07
Validation period			
N	821	821	821
NS value	0.943	0.972	0.968
R^2 value	0.957	0.976	0.974
RSME value	0.999	0.681	0.575
Observed mean	7.90	8.06	7.79
Simulated mean	7.82	7.95	7.82
Observed max. value	14.74	14.63	12.43
Simulated max. value	15.72	15.08	13.05
Observed min. value	0.71	0.98	1.78
Simulated min. value	0.02	1.07	2.70

Table A 6 Calibration and validation results for the simulated soil temperatures at Kindla for the three different soil profile depths

Parameter\Site	**Kindla 5 cm**	**Kindla 20 cm**	**Kindla 35 cm**
Calibration period			
N	2620	2500	2620
NS value	0.950	0.969	0.970
Observed mean	5.20	4.93	4.98
Simulated mean	4.84	4.82	4.80
Observed max. value	16.00	11.80	11.30
Simulated max. value	16.15	11.44	11.26
Observed min. value	-2.75	0.08	0.67
Simulated min. value	-1.07	-0.10	-0.05
Validation period			
N	1312	1252	1312
NS value	0.944	0.982	0.982
R^2 value	0.955	0.979	0.983
RSME value	1.136	0.478	0.405
Observed mean	5.69	5.12	5.81
Simulated mean	6.05	5.24	5.75
Observed max. value	15.50	11.50	10.60
Simulated max. value	15.82	11.09	10.84
Observed min. value	-1.10	0.82	1.61
Simulated min. value	-0.35	0.51	1.53

Table A 7 Calibration and validation results for the simulated soil temperatures at Gammtratten for the three different soil profile depths

Parameter\Site	**Gammtratten 5 cm**	**Gammtratten 29 cm**	**Gammtratten 40 cm**
Calibration period			
N	2153	2153	2153
NS value	0.966	0.974	0.976
Observed mean	4.15	4.16	3.88
Simulated mean	4.07	3.94	3.74
Observed max. value	15.00	13.40	12.70

Simulated max. value	15.41	13.69	13.23
Observed min. value	-0.39	0.18	-0.10
Simulated min. value	-0.95	-0.34	-0.38
Validation period			
N	1079	1079	1079
NS value	0.931	0.951	0.940
R^2 value	0.951	0.965	0.962
RSME value	1.134	0.830	0.883
Observed mean	4.00	4.01	3.74
Simulated mean	4.18	4.10	3.88
Observed max. value	13.10	11.60	11.00
Simulated max. value	14.64	13.06	12.62
Observed min. value	-0.72	-0.09	-0.27
Simulated min. value	-1.46	-0.43	-0.63

APPENDIX B

FUTURE SCENARIOS

Annual soil- and air temperatures

Table B 1 Simulated annual air– and soil temperatures (°C) for the ensembles scenarios 2061-2090, median year. Median, maximum and minimum scenarios from the ensembles are bolded

		Aneboda 10 cm		**Aneboda 32 cm**		**Aneboda 58 cm**		**Air temp.**	
No.	**Scenario**	Soil t.	Std	Soil t.	Std	Soil t.	Std	Air t.	Std
1	C4I_HAD	**8.39**	0.63	**8.62**	0.79	**7.96**	0.72	**10.14**	1.03
2	DMI_ARP	**7.27**	0.39	**7.11**	0.45	**6.60**	0.42	**8.23**	0.64
3	DMI_BXM	7.48	0.49	7.37	0.56	6.87	0.53	8.65	0.75
4	DMI_ECH	7.51	0.40	7.48	0.52	6.93	0.48	8.76	0.71
5	ETHZ	7.93	0.43	7.98	0.53	7.41	0.49	9.40	0.70
6	HC_HAD0	8.28	0.49	8.44	0.58	7.83	0.54	9.92	0.73
7	HC_HAD3	7.34	0.53	7.22	0.62	6.74	0.58	8.36	0.81
8	HC_HAD16	8.30	0.55	8.45	0.67	7.83	0.61	9.93	0.86
9	KNMI	7.66	0.40	**7.66**	0.49	7.08	0.44	**8.92**	0.68
10	MPI	8.24	0.52	8.25	0.63	7.65	0.58	9.61	0.84
11	SMHI_BCM	7.45	0.46	7.43	0.52	6.90	0.49	8.70	0.69
12	SMHI_ECH	8.17	0.48	8.27	0.55	7.70	0.51	9.68	0.72
13	SMHI_HAD	**7.75**	0.65	7.61	0.77	**7.13**	0.72	8.87	1.03
14	CNRM	7.38	0.53	7.33	0.62	6.77	0.58	8.48	0.88
15	ICTP	7.87	0.43	7.90	0.50	7.33	0.46	9.20	0.67
	Max.	8.39	0.65	8.62	0.79	7.96	0.72	10.14	1.03
	Min.	7.27	0.39	7.11	0.45	6.60	0.42	8.23	0.64
	Median	7.75	0.49	7.66	0.56	7.13	0.53	8.92	0.73
	Average	7.80	0.49	7.81	0.59	7.25	0.54	9.12	0.78

Table B 2 Simulated annual air– and soil temperatures (°C) for the ensembles scenarios 2061-2090, median year. Median, maximum and minimum scenarios from the ensembles are bolded

		Gårdsjön 0 cm		**Gårdsjön 10**		**Gårdsjön 25 cm**		**Air temp.**	
No.	Scenario	Soil t.	Std	Soil t.	Std	Soil t.	Std	Air t.	Std
1	C4I_HAD	**9.33**	0.67	**9.82**	0.77	**9.78**	0.85	**11.34**	1.16
2	DMI_ARP	8.12	0.37	8.38	0.42	8.23	0.44	9.22	0.68
3	DMI_BXM	8.33	0.52	8.63	0.59	8.45	0.63	9.51	0.89
4	DMI_ECH	8.28	0.40	8.57	0.48	8.41	0.51	9.50	0.75
5	ETHZ	8.80	0.37	9.12	0.43	9.07	0.45	10.25	0.69
6	HC_HAD0	8.86	0.40	9.23	0.47	9.16	0.51	10.45	0.67
7	HC_HAD3	**8.00**	0.47	**8.22**	0.54	**8.04**	0.57	**9.00**	0.81
8	HC_HAD16	8.85	0.51	9.23	0.58	9.17	0.64	10.45	0.88
9	KNMI	**8.47**	0.43	**8.79**	0.50	**8.64**	0.54	**9.80**	0.77
10	MPI	8.91	0.56	9.27	0.65	9.24	0.68	10.49	0.99

11	SMHI_BCM	8.36	0.48	8.64	0.54	8.53	0.58	9.61	0.82
12	SMHI_ECH	8.81	0.52	9.18	0.59	9.08	0.64	10.44	0.86
13	SMHI_HAD	8.57	0.65	8.88	0.76	8.76	0.81	9.98	1.11
14	CNRM	8.11	0.47	8.32	0.54	8.22	0.57	9.06	0.85
15	ICTP	8.40	0.39	8.74	0.44	8.58	0.48	9.56	0.67
	Max.	9.33	0.67	9.82	0.77	9.78	0.85	11.34	1.16
	Min.	8.00	0.37	8.22	0.42	8.04	0.44	9.00	0.67
	Median	8.47	0.47	8.79	0.54	8.64	0.57	9.80	0.82
	Average	8.55	0.48	8.87	0.55	8.76	0.60	9.91	0.84

Table B 3 Simulated annual air– and soil temperatures (°C) for the ensembles scenarios 2061-2090, median year. Median, maximum and minimum scenarios from the ensembles are bolded

		Kindla 5 cm		**Kindla 20 cm**		**Kindla 35 cm**		**Air temp.**	
No.	Scenario	Soil t.	Std	Soil t.	Std	Soil t.	Std	Air t.	Std
1	C4I_HAD	**6.89**	0.61	**6.81**	0.60	**7.76**	0.86	**9.03**	1.12
2	DMI_ARP	5.98	0.36	5.87	0.35	6.40	0.48	7.21	0.71
3	DMI_BXM	5.97	0.44	5.95	0.43	6.53	0.55	7.51	0.78
4	DMI_ECH	6.12	0.37	6.08	0.37	6.78	0.51	7.65	0.77
5	ETHZ	6.48	0.36	6.42	0.36	7.21	0.48	8.36	0.72
6	HC_HAD0	6.70	0.42	6.66	0.42	7.53	0.57	8.83	0.77
7	HC_HAD3	**5.91**	0.42	**5.81**	0.42	**6.25**	0.59	**7.14**	0.82
8	HC_HAD16	6.82	0.46	6.75	0.45	7.48	0.64	8.81	0.89
9	KNMI	**6.35**	0.35	**6.27**	0.33	**6.85**	0.48	**7.89**	0.62
10	MPI	6.64	0.47	6.57	0.46	7.32	0.64	8.50	0.85
11	SMHI_BCM	5.95	0.40	5.92	0.39	6.45	0.50	7.38	0.71
12	SMHI_ECH	6.66	0.43	6.59	0.42	7.37	0.56	8.72	0.78
13	SMHI_HAD	6.25	0.53	6.21	0.53	6.81	0.71	7.83	1.01
14	CNRM	6.10	0.50	6.03	0.49	6.62	0.62	7.54	0.95
15	ICTP	6.44	0.40	6.38	0.38	7.02	0.53	8.23	0.67
	Max.	6.89	0.61	6.81	0.60	7.76	0.86	9.03	1.12
	Min.	5.91	0.35	5.81	0.33	6.25	0.48	7.14	0.62
	Median	6.35	0.42	6.27	0.42	6.85	0.56	7.89	0.78
	Average	6.35	0.43	6.29	0.43	6.96	0.58	8.04	0.81

Table B 4 Simulated annual air– and soil temperatures (°C) for the ensembles scenarios 2061-2090, median year. Median, maximum and minimum scenarios from the ensembles are bolded

		Gamm. 5 cm		**Gamm. 29 cm**		**Gamm. 40 cm**		**Air temp.**	
No.	Scenario	Soil t.	Std.	Soil t.	Std.	Soil t.	Std.	Soil t.	Std.
1	C4I_HAD	**6.36**	0.86	**6.06**	0.78	**5.81**	0.76	6.56	1.35
2	DMI_ARP	5.18	0.38	4.99	0.36	4.77	0.35	4.79	0.75
3	DMI_BXM	**5.00**	0.44	4.82	0.42	4.60	0.40	4.71	0.77
4	DMI_ECH	**5.74**	0.51	5.48	0.47	5.24	0.46	5.62	0.92
5	ETHZ	5.89	0.42	5.65	0.39	5.41	0.38	5.79	0.79
6	HC_HAD0	6.00	0.52	5.69	0.46	5.45	0.45	6.17	0.89
7	HC_HAD3	5.01	0.44	**4.80**	0.41	**4.57**	0.40	**4.66**	0.94
8	HC_HAD16	6.32	0.72	6.04	0.65	5.78	0.64	**6.81**	1.19
9	KNMI	5.77	0.52	5.55	0.48	5.30	0.47	**5.64**	0.83

10	MPI	5.70	0.64	**5.51**	0.60	**5.25**	0.58	5.64	0.98
11	SMHI_BCM	5.07	0.40	4.89	0.37	4.66	0.36	4.82	0.75
12	SMHI_ECH	5.96	0.64	5.76	0.59	5.52	0.57	6.31	0.94
13	SMHI_HAD	5.14	0.54	4.97	0.50	4.75	0.48	5.19	1.02
14	CNRM	5.01	0.36	4.82	0.34	4.61	0.33	4.92	0.72
15	ICTP	5.79	0.53	5.52	0.48	5.28	0.47	5.64	0.73
	Max.	6.36	0.86	6.06	0.78	5.81	0.76	6.81	1.35
	Min.	5.00	0.36	4.80	0.34	4.57	0.33	4.66	0.72
	Median	5.74	0.52	5.51	0.47	5.25	0.46	5.64	0.89
	Average	5.60	0.53	5.37	0.49	5.13	0.47	5.55	0.90

Soil temperature seasonal variations

Table B 5 Simulated monthly average soil temperatures (°C) at Aneboda middle layer 2061-2090, median, maximum and minimum outputs; and observed monthly average soil temperature 1996-2008

Month	Median	Max.	Min.	Observed (1996-2008)
Jan	1.81	2.85	1.26	0.68
Feb	1.82	3.32	0.88	0.02
Mar	2.26	4.36	1.66	0.12
Apr	5.19	6.14	4.28	2.58
May	9.03	9.50	8.20	7.16
Jun	12.43	13.32	11.03	10.25
Jul	14.44	16.54	13.52	12.82
Aug	14.86	17.17	13.96	12.75
Sep	12.65	14.15	11.98	10.45
Oct	9.61	10.07	8.37	7.66
Nov	5.91	6.75	4.69	3.99
Dec	3.01	3.84	2.40	2.10

Table B 6 Simulated monthly average soil temperature (°C) at Gårdsjön middle layer 2061-2090, median, maximum and minimum outputs; and observed monthly average soil temperature 1996-2008

Month	Median	Max.	Min.	Observed (1996-2008)
Jan	3.71	4.43	3.46	2.01
Feb	3.63	4.96	2.91	1.76
Mar	4.12	5.87	3.48	1.83
Apr	6.18	7.40	5.74	4.23
May	9.36	9.96	8.80	7.58
Jun	12.19	13.03	11.09	10.26
Jul	14.17	16.19	13.29	12.40
Aug	15.23	17.53	14.41	13.24
Sep	13.54	14.98	13.00	11.65
Oct	10.65	11.45	9.79	8.63
Nov	7.45	8.38	6.48	6.03
Dec	4.83	5.59	4.60	4.09

Table B 7 Simulated monthly average soil temperature (°C) at Kindla middle layer 2061-2090, median, maximum and minimum outputs; and observed monthly average soil temperature 1996-2008

Month	Median	Max.	Min.	Observed (1996-2008)
Jan	2.62	3.01	2.00	2.08
Feb	2.06	2.50	1.53	1.56
Mar	2.04	3.03	1.72	1.30
Apr	3.36	4.21	2.78	1.63
May	5.71	5.94	5.13	4.23
Jun	8.33	8.64	7.37	6.70
Jul	10.18	11.07	9.38	8.82
Aug	11.32	12.67	10.58	9.87
Sep	10.60	11.82	10.12	8.97
Oct	8.67	9.26	7.95	7.02
Nov	6.15	6.69	5.31	4.55
Dec	3.99	4.45	3.44	3.19

Table B 8 Simulated monthly average soil temperature (°C) at Gammtratten middle layer 2061-2090, median, maximum and minimum outputs; and observed monthly average soil temperature 1996-2008

Month	Median	Max.	Min.	Observed (1996-2008)
Jan	0.32	0.58	-0.21	0.69
Feb	0.13	0.48	-0.17	0.55
Mar	0.13	0.57	-0.10	0.43
Apr	1.42	3.09	0.91	0.38
May	7.26	8.03	6.32	2.55
Jun	11.60	12.16	10.29	7.48
Jul	13.73	15.12	12.54	10.59
Aug	13.63	15.31	12.23	10.59
Sep	9.72	11.27	9.03	7.72
Oct	5.77	6.49	4.67	4.29
Nov	2.67	3.54	1.26	1.91
Dec	0.90	1.52	0.15	1.01

Snow depth seasonal variations

Table B 9 Simulated monthly average snow depth (mm) at Aneboda 2061-2090, median, maximum and minimum outputs; and simulated monthly average snow depth 1996-2008

Month	Median	Max.	Min.	Simulated (1996-2008)
Jan	24	41	5	77
Feb	16	47	6	56
Mar	12	28	0	50
Apr	2	9	0	4
May	0	0	0	0
Jun	0	0	0	0
Jul	0	0	0	0
Aug	0	0	0	0
Sep	0	0	0	0

Oct	0	1	0	1
Nov	2	5	0	7
Dec	10	31	5	44

Table B 10 Simulated monthly average snow depth (mm) at Gårdsjön 2061-2090, median, maximum and minimum outputs; and simulated monthly average snow depth 1996-2008

Month	Median	Max.	Min.	Simulated (1996-2008)
Jan	32	59	8	79
Feb	24	47	11	54
Mar	10	22	0	42
Apr	1	3	0	5
May	0	0	0	0
Jun	0	0	0	0
Jul	0	0	0	0
Aug	0	0	0	0
Sep	0	0	0	0
Oct	0	0	0	1
Nov	1	6	0	15
Dec	14	30	3	41

Table B 11 Simulated monthly average snow depth (mm) at Kindla 2061-2090, median, maximum and minimum outputs; and simulated monthly average snow depth 1996-2008

Month	Median	Max.	Min.	Simulated (1996-2008)
Jan	104	166	32	250
Feb	83	178	39	198
Mar	33	92	10	124
Apr	2	15	0	24
May	0	0	0	1
Jun	0	0	0	0
Jul	0	0	0	0
Aug	0	0	0	0
Sep	0	0	0	0
Oct	0	1	0	4
Nov	7	19	3	56
Dec	53	123	17	213

Table B 12 Simulated monthly average snow depth (mm) at Gammtratten 2061-2090, median, maximum and minimum outputs; and simulated monthly average snow depth 1996-2008

Month	Median	Max.	Min.	Simulated (1996-2008)
Jan	207	258	138	183
Feb	193	231	140	136
Mar	115	162	74	77
Apr	28	54	8	31
May	0	1	0	2
Jun	0	0	0	0
Jul	0	0	0	0
Aug	0	0	0	0

Sep	0	0	0	0
Oct	2	11	1	13
Nov	36	77	25	116
Dec	132	199	84	184