Lund University GEM thesis series nr 5

Climate Change Impact on Water and Temperature Conditions of Forest Soils: A Case Study Related to the Swedish Forestry Sector

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2014
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Climate Change Impact on Water and Temperature Conditions of Forest Soils: A Case Study Related to the Swedish Forestry Sector

by

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Thesis submitted to the department of Physical Geography and Ecosystem Science, Lund University, in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation for Environmental Modelling and Management

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Disclaimer

Course title: Geo-information Science and Earth Observation for Environmental Modelling and Management (GEM)

Level: Master of Science (MSc)

Course duration: January 20*14* until June 20*14*

Consortium partners:

The GEM master program is a cooperation of departments at 5 different universities:
University of Twente, ITC (The Netherlands)
University of Lund (Sweden)
University of Southampton (UK)
University of Warsaw (Poland)
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Abstract

Climate change concerns all ecosystems and forestry is one of vulnerable sectors. The Intergovernmental Panel of Climate Change (IPCC) projects that global warming, caused by anthropogenic emissions of greenhouse gases (GHG), might cause the rise of global surface temperature (compared to pre-industrial times) exceeding 2 ^{o}C by the year 2100.

Forestry is of major economic importance in Sweden. Therefore projected climate change and its impacts are of great concern for the Swedish forestry sector.

Increasing atmospheric CO_2 concentrations and warming temperatures in northern latitudes are projected to have positive effects on forest growth and wood production. Apart from increased length of growing period, climate extremes might negatively affect trees. Negative impacts are very likely to outweigh positive ones. In particular, ground frost is of great importance for trees anchorage capacity, which, in its turn is vital for forests' predisposition to storm damage and damage caused by heavy machines. The major objective of this work was to analyse the risk of storm damage and risk of driving damage caused by heavy machines on trees.

In this work, records of storm damage in Sweden during the 20th century and the historical climate data (based on GCM (General circulation model) run) for the period 1950-2005 were used to analyse the connection between storm damage and soil hardiness during October-May period. The influence of frozen soil on forests predisposition was analysed. It was found that the storm damage mainly occurred in conditions of unfrozen soil and high amount of water content in soil.

Climate model data, based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) was used in this work to analyse possible changes in forest soil conditions for the period October-May in the twenty-first century, under the tree RCP (Representative Concentration Pathways) scenarios. Analyses showed that the changing climate in the twenty-first century might have the following impacts on water and temperature conditions of forest soils in southern Sweden: 1) soil temperature might increase throughout the country, being the highest for the most pessimistic RCP8.5 scenario; 2) snow cover might decrease substantially by the end of the century under all tree RCP scenarios reaching to 0 cm in the south; 3) soil moisture might increase, being higher for the RCP8.5 scenario; 4) soil hardiness might decrease especially under the most pessimistic RCP8.5 scenario, being close to 0 cm at the end of the century. These factors can possibly lead to more adverse impacts on forestry, by affecting trees' predisposition to climate induced damages, such as severe wind storms, as well as human induced damages, such as heavy machinery use for clear cutting, thinning etc.

The results of this work may contribute for the future planning and management of forest practices. It is important to consider the projections for the future climate and its impacts, in order to make appropriate adaptation and mitigation measures towards sustainable management in the forestry sector, which is of great socio-economic importance for the country.

Keywords: climate change, climate model, ground frost, forest management, Swedish forestry, soil temperature, wind storm.

Acknowledgements

This Master program and thesis work would not have been possible without the help of many people. I would therefore like to express my sincere gratitude to all of them.

First, I am immensely thankful to my supervisor Anna Maria Jönsson for her continuous support, motivation and encouragement over the last several months. Thank you so much for your recommendations, criticism and corrections of the thesis. Thank you for helping and guiding me throughout the entire study period. Your patience and support was essential for my success.

I would like to thank the examiners, Harry Lankreijer and Peter Eliasson for detailed reviews of my work, for your support, patience and guidance during the writing process of this thesis.

Dr. Michael Weir, Prof. Andrew Skidmore, Prof. Petter Pilesjö and Prof. Ted Milton - I am infinitely grateful to you for accepting me to this MSc program. Thank you for giving me the chance to study this Master program at two of the best European universities. The knowledge, skills and experience I gained during these two years have changed my life and my future on both professional and personal levels.

My sincere thanks goes to my friends and coursemates at NRM department of ITC faculty. Pandu, Satish, Efrén, Yuan, Jingyi, Michele, Jing, Tereza, Apri, Titus, Wigger, Judith, Tawanda, Joseph, I am so glad I had a chance to study with all of you, to share knowledge and experience. Thank you for making the study process joyful. Mireille, Samwel and Hala, I will never forget the laughter we shared during the coffee breaks and lunch times. Thank you everyone for your friendship and support during those hard times. My dear friends, those memories mean a lot to me.

I would like to thank my coursemates and friends in Lund. Tatiana and Monika, I enjoyed working with you on group-projects. Tanya, thank you for your kind support during my studies and especially during the thesis writing period. I am glad I met a person like you with who I could share my cultural interests. I hope we can meet again in the future. My flatmates Marilia, Becci, Mariana and Assiya – I was lucky and glad to have neighbours like you. I had fun sharing cooking experiences with you in the kitchen, having conversations and spending sleepless nights together while studying and preparing for exams. I miss you all.

I want to mention my best friend Arpine: being far from you these two years made me realise how much your friendship means to me. Thank you for always encouraging me. Thank you for your support and for always being there for me.

Finally, I have some special words of thanks to people without who I would never be able to accomplish my dreams and goals.

I am highly indebted to my parents Gohar and Kamo, my brothers Ando and my grandmother Marselia for their unconditional love, encouragement and support. Mom, I would like to extend my gratitude to you for bearing psychological cost of being lonely at home during these two years. I missed all of you. I am happy I can finally be close to you, at home.

Lars-Johan Brännmark, two years ago I took a road, which I was hoping would lead me to a great professional future. But I had never imagined that the road would bring me to the love of my life. You are my inspiration and motivation to study science, to go further in my chosen profession and to follow my dreams. Thank you for your tremendous contribution towards my study. Thank you for being in my life.

I believe that this journey called GEM has changed my life forever…

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List of Abbreviations

AR5 The Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
CMIP5 Coupled Model Intercomparison Project Phase
CORDEX Coordinated Regional climate Downscaling Experiment)
CO_2 carbon dioxide
E East latitude
ECA European Climate Assessment
ESG Earth system grid
GCM General Circulation model
GHG greenhouse gas
IPCC Intergovernmental Panel on Climate Change
JFMAM January-February-March-April-May period of a year
N North latitude
OND October-November-December period of a year
ppm concentration (of carbon dioxide) in parts per million
RCA4 New version of Rossby Centre regional atmospheric model
RCM Regional climate model
RCP Representative Concentration Pathways
SMHI Swedish Meteorological and Hydrological Institute
WCRP World Climate Research Program
W/m^2 watts per square metre

Chapter 1

1. Introduction

1.1 Climate change

Changing climate has direct and indirect impacts on forests. Climate induced disturbances can directly lead to tree mortality, e.g. due to forest fires, drought, windstorms and hurricanes. Indirect disturbances, which also influence tree mortality, include insect and pathogen outbreaks, introduced species, as well as human-induced damage such as damage caused by heavy machines during clear cutting, timber harvesting and thinning.

Climate observations have proven the existence of global warming; in their studies Hansen et al. (2006) show that global average temperature has increased by 0.8 ^{o}C since 1900 and the 12 hottest years observed globally since 1880 all occurred between 1990 and 2005. Future climate scenarios of the fifth assessment report (AR5) of IPCC (J.H. Christensen et al., 2013) suggest that by 2100 global mean surface temperature could increase by about 1–3.7 ^{o}C.

Changing climate can have negative impact on many ecosystems. In particular, forests are sensitive to climate change. Because of the long life-span of trees, forests are not capable to rapid adaptation to environmental changes. There are several factors which influence forests. Those factors can act independently or in combination with others. Some of the major disturbance factors considered are high and low soil temperature, the soil water depth, ground frost and wind storms (Coutts, 1983; Moore, 2000; Tierney et al., 2001).

1.3 Positive and negative impacts of changing climate on forest ecosystems

Some studies indicate that apart from negative effects, the changing climate could also positively influence forest ecosystems. In particular, increasing temperature and CO_2 concentrations were predicted to lead to prolonged growing season and increase of wood production in boreal forests (Kellomäki and Kolström, 1994; Lindner et al., 2010; Väisänen et al., 1994). However, other studies indicate that negative impacts of changing climate can be more than the positive ones and those negative impacts may be even larger than expected (Schröter et al., 2005). Work by Körner (2004) suggest that the positive impacts of climate change are overestimated as they ignore some feedbacks. As it was stated in the IPCC's 4th assessment report (Metz and Davidson, 2007), changing climate could also cause changes in the occurrence and level of extreme climate events, such as changes in frost conditions, water stress and damaging windstorms. These changes could lead to an increased frequency of weather events beyond plant physiological tolerance thresholds, potentially resulting in stress, damage, and mortality of trees.

A study by (Rummukainen, 2003) showed that warming could be larger in the northern hemisphere compared to the southern, and even stronger in winter, and a study by (Houghton, 2009) showed that precipitation in the north is expected to increase in the future. Many studies related to impacts of climate change on Swedish forestry were conducted by e.g. (Nilsson et al., 2004) and Bengtsson and Nilsson (2007). These studies suggest that climate extremes have caused disturbances in Swedish forests in the past and in the future the damage to the forests can be even more drastic. Around 70% of Sweden's territory is forest, and it is one of the country's most important resources, playing a central role in the economy ("Swedish Wood," 2012). The forest resources must be used in a way that sustains productivity, renewal and growth. Therefore, analysis and assessment of impacts of climatic events on trees have great importance for preserving Swedish forestry and for better management adaptation practices. Strategies for adaptation and reducing forest damage include planting of tree species that are better adapted to warm environmental conditions (Resco et al., 2007).

1.4 Aim and objective of the thesis

The objective of this work was to analyse the impact of climate change on soil water and temperature conditions in Sweden, focusing on the southern part; and to make projections for future conditions of forest soils and possible damages under the changing climate.

The aim of the thesis was**:**

- Analyse major factors affecting forests, i.e. soil temperature, snow cover, soil moisture and frozen soil over the last 60 years (during October-May season);
- Compare those results with historical storm damage data ;
- To calculate impact indices based on latest scenario projections; RCP2.6, 4.5, 8.5 (IPCC, 2013b) and analyse the possible impacts of changing climate on forests in South;
- Compare climate model data for tree different RCP scenarios with historical data in order to assess the climate change signal;
- Suggest some adaptation actions.

Chapter 2

2. Background

2.1 Climate change and IPCC projections

In recent years, the issues of climate change and its impacts have been actively discussed in environmental science and politics including general media and public. Changes in many extreme weather and climate events have been observed historically. Research conducted for the last century indicated that it is very likely that the number of cold days and nights has decreased since 1950 and the number of warm days and nights has increased on the global scale. It is likely that the frequency of heat waves has increased in large parts of Europe (IPCC, 2013b).

Projections were adopted by the IPCC in its fifth Assessment Report for the end of the twenty-first century, compared to the end of twentieth century (pre-industrial times) (IPCC, 2013a). The group of new RCP scenarios was used for the new climate model data analysis. RCP8.5 is considered as high emissions (most pessimistic) scenario, under which CO_2 emissions were projected to be three times more by 2100 and with no implementation of climate policies. Under RCP 4.5, which is considered as intermediate emissions scenario, CO_2 emissions were projected to increase slightly and reforestation programs should take place. According to the RCP2.6 less emissions scenario (most optimistic scenario) CO_2 concentrations would peak by 2050, and then decline to the pre-industrial value by the year 2100. According to the report, temperature increase on average in the years 2081-2100 (compared to the values in 1850-1900), might be by 1, 1.8 and 3.7 ^{o}C higher for RCP2.6, RCP4.5 and RCP8.5 scenarios respectively.

Research done with different climate models showed that in the coming years and throughout the twenty-first century the warming might be much higher in northern latitudes than in southern latitudes and warming might be more considerable in winter season

(Houghton, 2009). In addition, precipitation in northern latitudes might increase throughout the year (Metz and Davidson, 2007). Climate models show significant agreement for all emission scenarios of warming in Europe (Goodess et al., 2009; Kjellström et al., 2011). It was projected that strongest warming in Southern Europe might be in summer, and in Northern Europe strongest warming might be in winter.
As it was mentioned in the latest IPCC report (IPCC, 2013a), increasing air temperature in the higher latitudes of the northern hemisphere, is predicted to increase further in the future. More severe changes are predicted to occur in winter seasons (J. Christensen and Christensen, 2007).

2.2 Forests and factors influencing tree damage

Soil conditions, e.g. moisture, hardiness and soil temperature are important factors for predisposition of trees to damage. Heavy machinery, used for timber harvesting, are known for causing tree root mortality when driving on wet soils. Wind storms are known for causing serious threat to forests: during severe storms trees usually become uprooted if the soil is wet and unfrozen. In changing climate, increasing precipitation in autumn, decrease of snow cover and increase of soil moisture in winter might lead to higher damage compared to the situation of today.

Table 1 comprises the key aspects of some previous findings indicating changes in soil conditions and wind storms.

Table 1. Key aspects of some previous findings indicating changes in soil conditions and wind storms.

Previous findings	Authors
Increase of average soil temperature by 0.9 –1.5°C by the end of twenty first century	(Mellander et al., 2007)
Decrease of snow cover during winter	(Jylhä et al., 2008), (Gregow et al., 2008)
Decreased soil frost in winter	(Mellander et al., 2007), (Gregow et al., 2008), (Peltola et al., 1999)
Increased soil moisture	(Räisänen and Joelsson, 2001)
Wind damage recorded in the past	(Coutts, 1983; Moore, 2000), (Nilsson, 2008)
Projected changes on the frequency and strength of winds in the future	(Hueging et al., 2013), (Nolan et al., 2012), (Rockel and Woth, 2007), (Blennow and Olofsson, 2008)

2.2.1 Soil conditions causing tree damage

Tierney et al. (2001) showed that changes in the soil temperature regime during winter might affect root mortality in the future. SWECLIM regional climate modelling programme (Mellander et al., 2007) predicted that average soil temperature could increase by 0.9 –1.5°C by the end of twenty first century. Changes in soil temperature depend on climatic conditions such as snow cover. In northern regions of Sweden distinct winter seasons and long periods of snow cover are common. Some studies found that warming climate in the north might lead to a decrease of snow covered periods during the winter season in Sweden (Jylhä et al.,

2008). A study conducted for Finland region by Gregow et al. (2008) also projected decrease in snow cover. Because snow plays a “blanketing” role for the soil, therefore no snow cover in winters can lead to increased ground frost.
In fact, some studies projected changes in ground frost regimes. Mellander et al. (2007) projected more soil freeze–thaw cycles by (31 – 38%) in Sweden by the end of the century. Studies related to soil hardiness for the region (Gregow et al., 2008) indicated that the length of the frozen soil period would decrease all over Finland. Another study Peltola et al. (1999) projected that soil frost period might decrease from 4–5 months to 2–3 months per year in southern Finland.

If freezing of soil can increase soil stability, in contrast, high soil moisture content caused by increased precipitation and temperatures can weaken soil stability (Combe, 1998). Räisänen and Joelsson (2001) projected that due to warming climate winter precipitation could more likely fall as rain in northern and central Europe. This means that in conditions of rainy season soils might be wetter in winters in the future.

Overall, in the changing climate, the changes in temperature and water conditions of soils may have even greater impact on Swedish forests causing damages such as tree root mortality.

2.2.2 Wind storms and caused damage on trees

Vulnerability of trees to wind throw largely depends on soil hardiness and trees’ anchorage capacity. In fact, when soil is waterlogged, both shear strength and the root–soil bond are reduced, and therefore, the entire system fails more easily during wind loading (Coutts, 1986). In dry soils trees tend to be better anchored but the stem breaks during loading, whereas trees in waterlogged soils are usually uprooted (Coutts, 1983; Moore, 2000).

In their work Resco et al. (2007) showed that recorded forest storm damage has significantly increased since the beginning of the last century. The authors mention, that those drastic events could be the signs of changing climate. Nilsson (2008) conducted a research on windstorms in Sweden for the years 1900-2008. It was found that relatively severe storm damage in Sweden occurred at second half of 20^{th} the century. The most severe damage was caused by Gudrun storm (in January 2005): the damage equals to 2/3 of the total recorded forest damage for the last 100 years.

Several studies and model simulations have been conducted in order to find out possible changes on the frequency and strength of winds in the future. According to works by Hueging et al. (2013), Nolan et al. (2012), Rockel and Woth (2007), the wind energy potential in Northern Europe may increase during winter and decrease in summer especially after 2050. Research by (Blennow and Olofsson, 2008) for Sweden showed that under changing climate (under 7 scenarios) windiness for southernmost Sweden might increase by the end of twenty-first century. This means that damage caused by wind storms can be even higher in the future.

2.4 Economic importance of forests in Sweden, adaptation and mitigation actions

Sweden has Europe's second largest forested area after Finland. Sweden's forests cover around 23 million hectares ("Nordic Family Forestry," 2004). If this area is calculated according to international forest land definitions, then it is 27 million hectares, corresponding to 66% of the whole land area. Sweden's pulp and paper industry is the third largest in Europe and it supplies more than one tenth of the demand for paper in the EU countries. According to the statistics of Swedish Forest Agency ("Swedish Forest Agency," 2002) total area of old-growth forest decreased from 1985 to 1996, and has increased afterwards. The volume of hard dead wood per hectare has also increased since 1996. Currently Sweden accounts for 7% of the total export value of forest products worldwide.

Swedish forests are a considerable sink of carbon. Around tree billion tonnes of carbon are in the trees and around 6 billion tonnes in the forest soil ("Nordic Family Forestry," 2004). The renewable energy supply of the country has increased considerably since the

1970s, mainly through the use of biofuels. Around 80% of generated biofuels are forest-based ("Nordic Family Forestry," 2004). Recent studies indicate that wood production in the country might be increased by 20% by the year 2050 in case of improved forest management.

Sweden is one of those countries where environmental issues are considered at the political level. Country's economy largely depends on forests and therefore proper management practices play an important role, not only from the state of the forest but also for the country's national economy and livelihoods.

Managing forest ecosystem in changing climate is vital for the forest ecosystems and for the country's overall development. Changing and/or improving timber harvesting and clear cutting techniques (heavy machinery) must be incorporated in climate change adaptation actions in order to reduce to damage to forests in the future. In addition, incorporating planting of tree species with other management practices can increase the resilience and sustainability of forests.

Analysis of climate model data can give essential evidence on possible changes and impacts. Therefore, modelling approaches integrated into stakeholder and decision–support systems can become an important tool for implementing better management and adaptation policies.

Chapter 3

3. Materials and Method

3.1 Workflow of the thesis

Figure 1 shows the logical workflow of current thesis. This paper is a modeling study, organized as follows. In the first two chapters (Introduction and Background – upper, green part in the flowchart) impact of climate change on forest ecology is discussed, factors affecting forest properties are discussed and possible adaptation actions for better forest management in Sweden. In Chapter 3 (Materials and Methods – grey part of the flowchart) climate model data used in this work are described. In Chapter 4 (light blue part of the flowchart) results of current work are presented, i.e. soil parameters affecting forest properties. Chapter 5 discusses current results and related results of previous works (yellow and red parts of the flowchart). In Chapter 6 and Chapter 7 conclusions of current findings and needs for further research are presented.

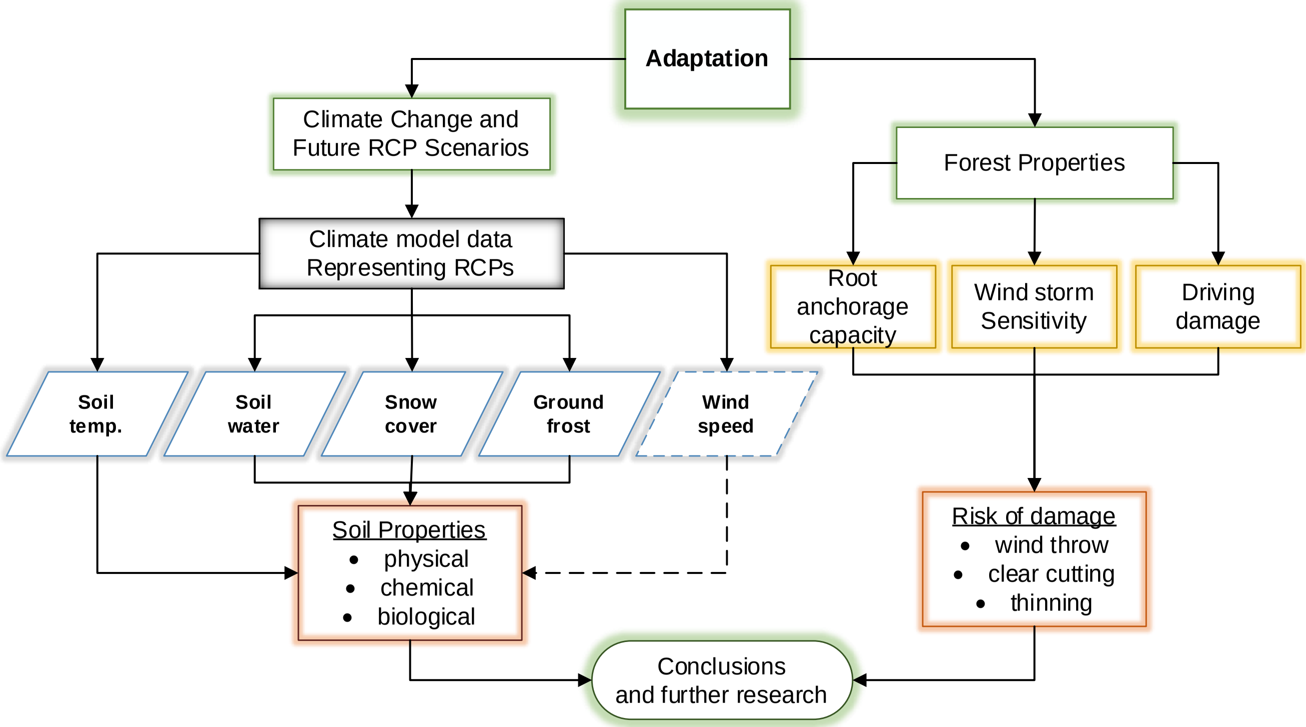

Figure 1. Flowchart representing the logical sequence of the work. Introduction and Background (Chapters 1 and 2) are presented in upper green color, Materials and Methods (Chapter 3) is presented in grey color, Results (Chapter 4) is presented in blue color, Discussions (Chapter 5) is presented in yellow and red colors, Conclusions and Future Research (Chapters 6 and 7) are presented in green at the bottom of the flowchart.

3.2 Climate model data and method

Table 2 shows the climate data used in this research. Climatic data were produced by the Swedish Meteorological and Hydrological Institute's (SMHI) climate research at the Rossby Centre ("SMHI," 2012). SMHI is part of CORDEX (Coordinated Regional climate Downscaling Experiment) initiative which is sponsored by World Climate Research Program (WCRP) for organizing an international coordinated framework for producing improved group of regional climate change projections for input into impact and adaptation studies within the AR5 ("CORDEX," 2009). The climate scenarios were produced using the regional climate model RCA4. The modelled data was based on the Coupled Model Intercomparison Project Phase 5 (CMIP5), simulations of the future RCP scenarios 2.6, 4.5 and 8.5.

The RCPs cover group of emission scenarios with specific climate mitigation policies (IPCC, 2013b). For example, RCP2.6 assumes that global annual greenhouse gas (GHG) emissions (measured in CO_2 equivalents, i.e. ppm) will peak by the year 2020, and then will declining to 2.6 watts per square metre (W/m^2) by 2100; emissions in RCP 4.5 will peak around 2040, and then decline to 4.5 W/m^2; and in RCP 8.5, emissions will continue to rise throughout the 21st century reaching to 8.5 W/m^2 (Meinshausen et al., 2011). RCP2.6 is considered as the most optimistic scenario (based on strong mitigation efforts in parallel with active removal of atmospheric CO_2), whereas RCP8.5 is based on minimal effort to reduce emissions and is considered as the most pessimistic scenario.

The historical data for the period 1950-2005 was based on GCM (General circulation model) model run. The evaluation data for the period 1980-2010 was based on the RCM (Regional climate model) driven by observed data.

Table 2. Data used in this work.

General circulation model (GCM)	**Regional climate model (RCM)**	**Climate model data**	**Time periods**
EC-Earth (ESG (Earth system grid) data)	RCA4 (New version of Rossby Centre regional atmospheric model)	Evaluation	1980-2010
		Historical	1950-2005
		RCP2.6	2010-2099
		RCP4.5	2010-2099
		RCP8.5	2010-2099

Four variables analysed in this work are presented in the table 3. In the simulation model soil temperature was calculated within two meters depth. Soil moisture and frozen water in soil were calculated within one meter depth.

Table 3. Four variables analysed in this work.

soil temperature	soil temperature expressed in ^{o}C
snow cover	amount of snow expressed in mm (depth over square meter)
soil moisture	total water content in soil expressed in mm (depth over square meter)
frozen soil	content of frozen water in soil expressed in mm (depth over square meter).

After extracting the data, above presented four variables have been computed in this study, by using MATLAB R2013a (MathWorks, 2013). Data were plotted on grid cells of 0.44 degrees, with 50 gridcells in longitude and 55 in latitude. Generated maps of variables include the area from 50N^{o}/5^{o}E to 72^{o}N/33^{o}E (figure 2). The forested area of each grid cell was represented by a number of patches that would have the same climatic and soil conditions.

In this study it was decided to focus on October-May season. The reason for choosing autumn-winter-spring season was because the weather events (rainy seasons, snow falls, wind storms) during that period are stressful for the forests: soil condition are influenced by weather and therefore threaten forests. For calculating regional mean values of the variables, the average values of all grid cells was calculated, for all four variables.

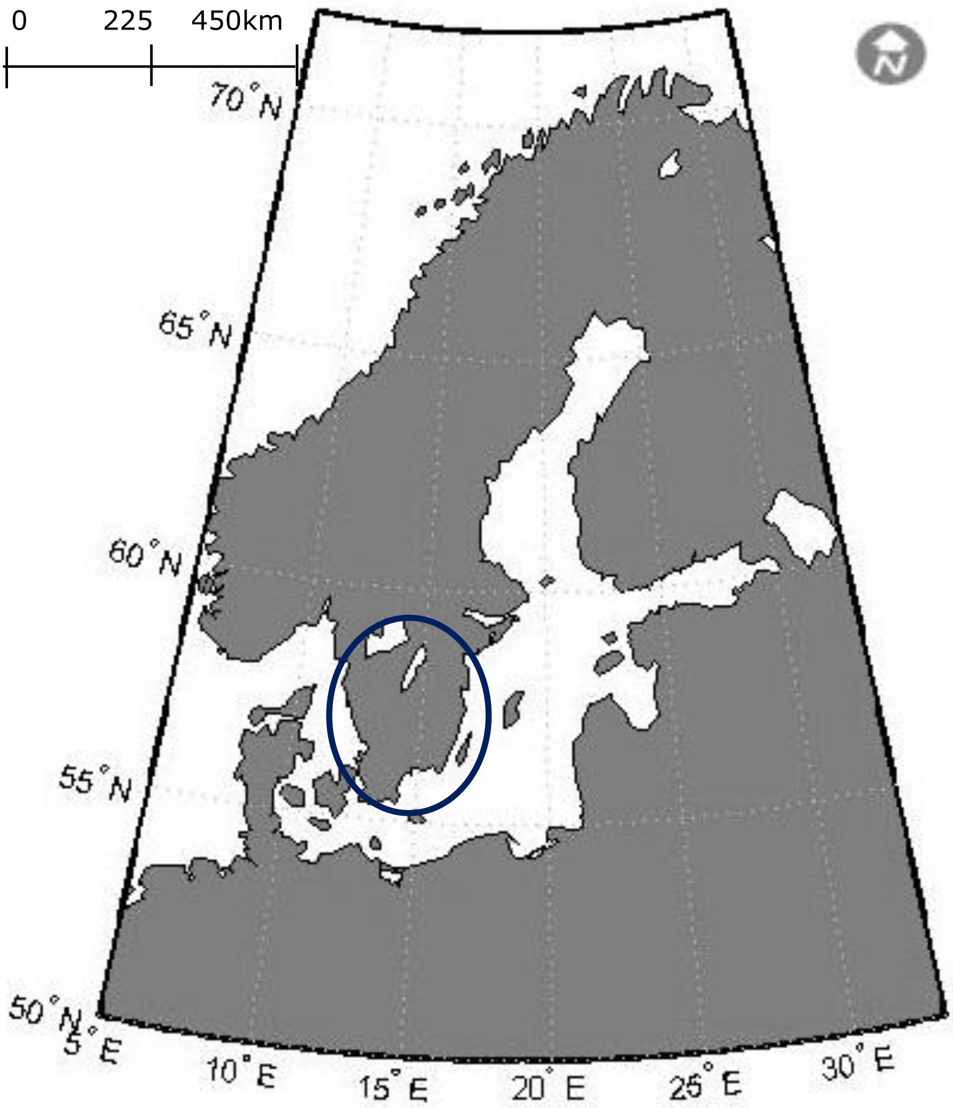

Figure 2. The map is an example of generated maps. The entire area covers the North Europe: 50ºN/5ºE to 72ºN/33ºE. Study area is Sweden, mainly southern Sweden (area inside of the dark blue circle).

3.3 Generated maps of four variables

For model evaluation and calibration, time-series of all four environmental variables for the period of 1980-2010 was compared to historical data of 1950-2005 (figures 4, 5, 6).

For the analysis of relationships between the damage caused by severe storm events and soil conditions in the past, recorded severe storms events was analysed. Historical data of damage caused by severe storm events for the years 1954-2007 was taken from the work of authors Nilsson et al. (2004) and Nilsson (2008). A scattered graph was created (figure 3) which shows the distribution of damages caused by the most severe wind storms throughout the year - days 1 to 366 of each year for the period of 1954-2007. Most severe wind storms causing severe damage were regarded winds of 30m/s and higher speeds.

Analysis of climate model data representing tree RCP scenarios was analysed for tree different time periods, namely, 2011-2040 (named as 1st period in the figures), 2041-2070 (named as 2nd period in the figures), and 2071-2100 (named as 3rd period). In order to detect more specific changes of four variables during October-May season it was decided to divide the entire season into two parts: October-November-December season (named as OND in the text and figures) and January-to-May season (named as JFMAM in the text and figures).

Taking into account that comparisons between the results for the first and third periods would give much more evidence, and in order to avoid having too many figures, it was decided to include the maps generated for the second period (2041-2070) in the Appendix (figures 21 to 25). For the same reasons, it was decided to include only maps representing most optimistic RCP2.6 and most pessimistic RCP8.5 scenarios and exclude the maps generated for the RCP4.5 scenario from the discussions (figures 16 to 20). All generated maps that were not included in the results and discussion chapters, are presented in the Appendix (figures 16-25).

3.4 Statistical boxplots

Statistical boxplots were created to better show the variation between the results representing tree RCP scenarios for the southern part of Sweden. It was decided to take one representative grid cell in the south Sweden (18 latitude, 25 longitude, which approximately corresponds to 56ºN/14ºE on the map, figure 2) and create statistical boxplots showing variations of four parameters under RCP2.6 and RCP8.5 scenarios during two seasons, OND and JFMAM.

In order to show more vital changes and to avoid having too many boxplots, it was decided to include the boxplots representing only the first and third periods of the twenty-first century.

Chapter 4

4. Results

4.1 Analysis of data representing current climate conditions

The generated maps for the historical period and evaluation period for soil temperature, snow cover, frozen soil and soil water are presented in the figures 3 and 4. It was observed that historical data and evaluation data provided similar results. The model shows good correlation with the historical data.

The scattered graph shows that very few storm damage took place in the April-September season (tree events in the first half of 1970s, 1 event in 1984, and 1 in 1997). Most damage events took place in the period September-to-March (24 events), from which the highest number of damage events was during September-to-December, namely, 14 events. It can be seen also, that the number of storm events with damage to forests increased since 1980s to present.

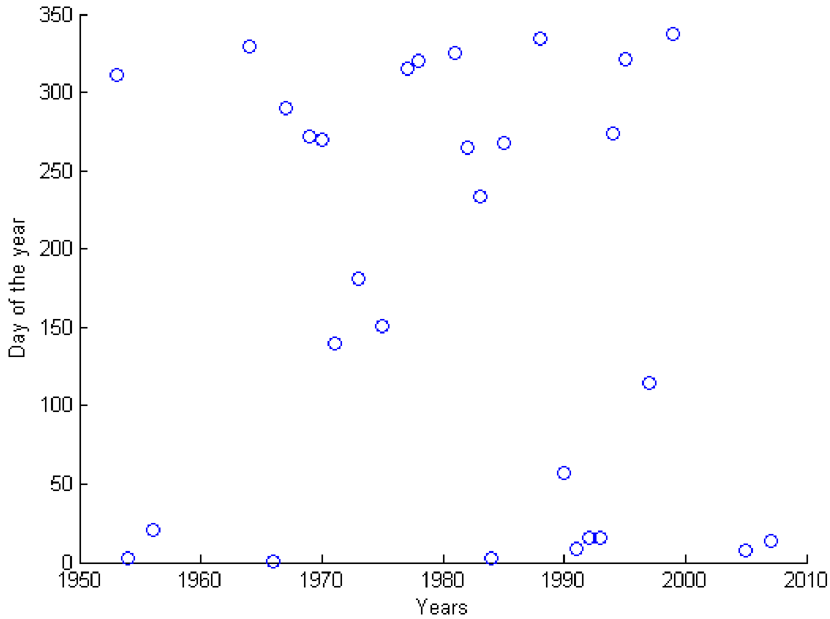

Figure 3. Scattered graph of most severe storm damage in Sweden, from 1950-2007 years. x axis shows the years, and y axis shows the days of the year. Historical data of damage events caused by severe storms for the years 1954-2007 was taken from the work of authors Nilsson (2008) and Nilsson et al. (2004).

In order to see the relationship between the damage caused by severe winds and soil moisture and frost, maps for OND and JFMAM were generated for those variables (figure 6). The average depth of frozen water in soil in JFMAM was 7 cm, whereas in OND it was around 1 cm. The average soil water depth was higher in OND, namely 52 cm, than in JFMAM, which was around 42 cm.

From the historical data it was found that mean soil temperature in southern region was around 0 ^{o}C, and in central parts -5 ^{o}C. The lowest temperatures, ranging from -5 to -13 ^{o}C, were found in northern parts (figure 4). Historical data showed that in the southern parts, the depth of snow cover was around 2 cm. Relatively more snow was found in central and northern parts, ranging from 1-10 cm. In the historical period, the averaged (over 8 months) amount of frozen soil in the study region did not exceed 5 cm, while in the central part it was 5-20 cm and in northern parts, 20-25 cm and above. The averaged soil-water map of that period shows that the water content in soil ranged 38-45 cm in the south, which was higher in central and northern regions, reaching to approximately 48 cm.

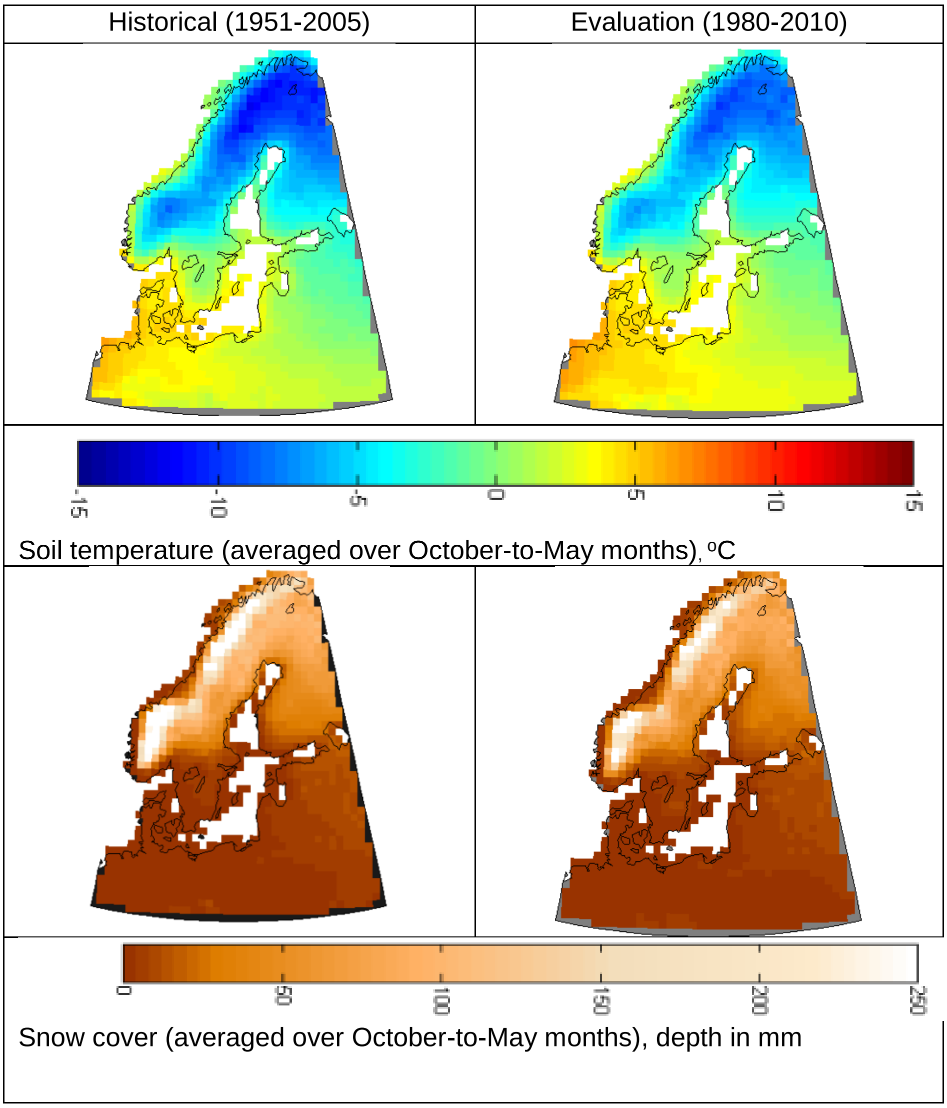

Figure 4. Climate model data for historical period (1951-2005) compared to model evaluation (1980-2010) for the October-to-May season. Time-step of the model stimulation was one year. The maps in the upper row show average (over October-to-May months) results for soil temperature (ºC), the maps in the second row show average results for the snow cover (mm depth).

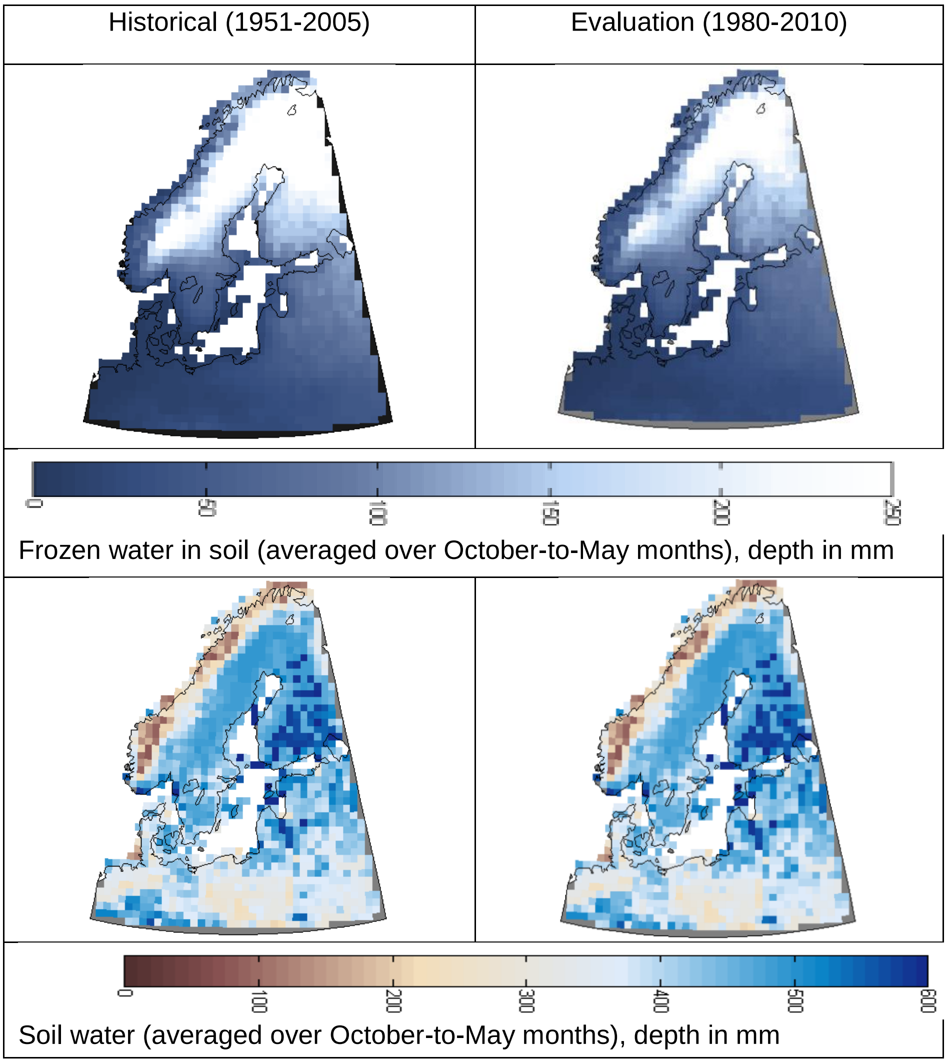

Figure 5. Climate model data for historical period (1951-2005) compared to model evaluation (1980-2010) for the October-to May season. Time-step of the model stimulation was one year. The maps in the first row show average (over October-to-May months) for the frozen water in soil (mm depth), and the maps in the second row show average results for the soil water (mm depth).

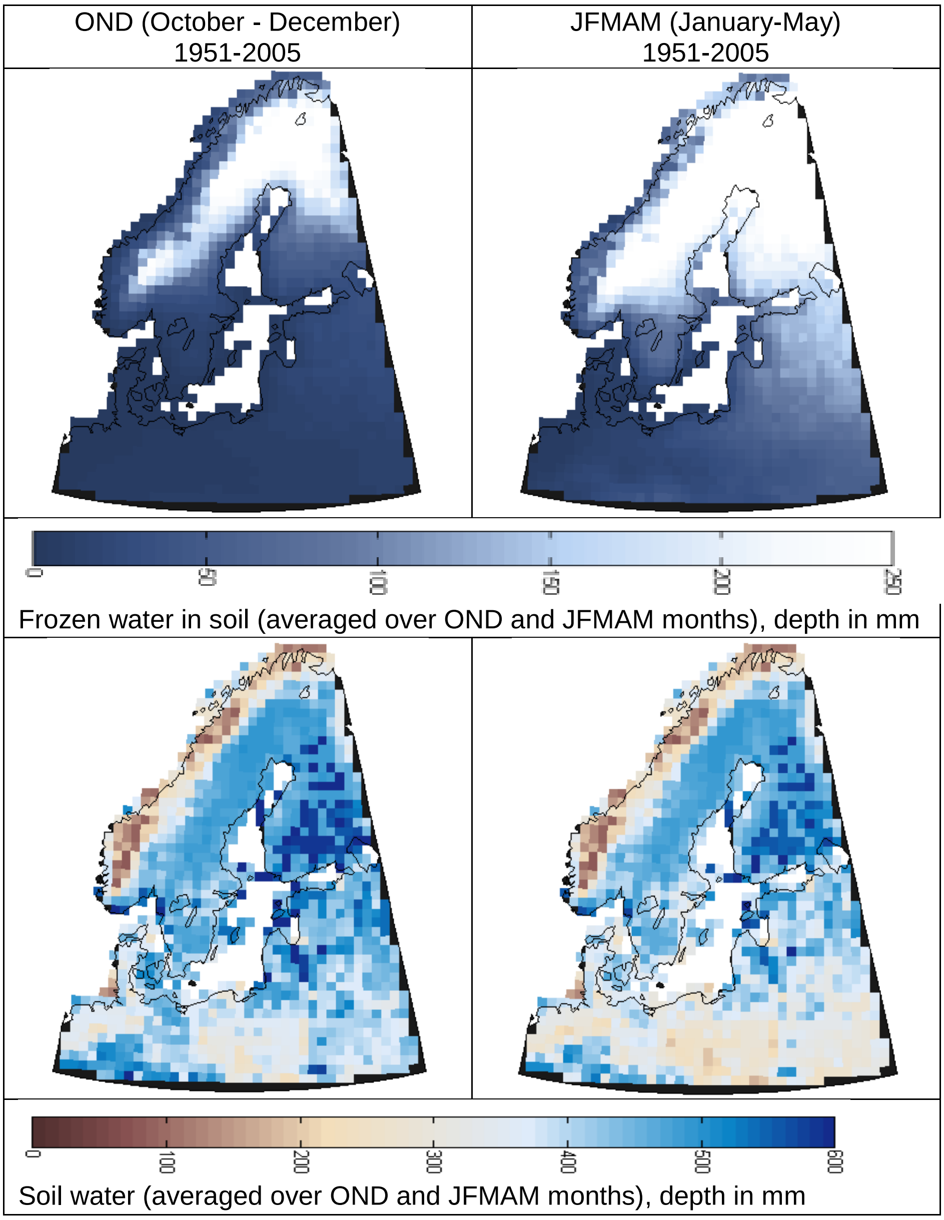

Figure 6. Frozen soil water and total soil water content for historical period (1951-2005 years). Time-step of the model stimulation was one year. The maps on the first column show average results for frozen water in soil during OND and JFMAM, the maps in the second column show average results for the soil water during OND and JFMAM.

4.2 Climate model data representing future RCP scenarios

4.2.1 Analysis of data representing the first period, 2011–2040

Climate model data for the average soil temperature in October-May period showed increase under the tree RCP scenarios (compared to the historical period), ranging from 0.5 to 3.5°C for RCP2.6 and 1 to 5.5 °C for RCP8.5 (figure 7). For RCP4.5 scenario the likely range was 0.5 to +5 °C (figure 16, Appendix).

Snow cover maps (figure 8) for the same climate data set showed almost no snow depth, or close to 0 cm in southern region. Central and northern parts showed considerable decrease of snow depth, albeit being much less for RCP8.5 scenario than for the optimistic RCP2.6 scenario.

Maps of frozen water in soil for the October-May period (figure 9) showed decrease of the depth of frozen water in soil for both RCP2.6 and RCP8.5. In particular, it was detected decrease from the historical 5 cm depth to: 1) 3.6 cm under optimistic RCP2.6 scenario and 2) 2.7 cm under the worse RCP8.5 scenario. The results for RCP4.5 were close to 3.2 cm (figure 18, Appendix).

The seasonal variations of soil moisture (figures 9 and 10) showed that it might be relatively less in OND than in JFMAM (as it was the case for the historical period). However, in case of RCP2.6 scenario increase of water depth from OND to JFMAM might be slightly higher, namely 42 to 48 cm, than for RCP8.5, rising from 42 to 46 cm.

4.2.2 Analysis of data representing the second period, 2041–2070

It was found that average soil temperature might rise from historical 0 °C to 1 in case of RCP2.6 and to 4 °C in case of RCP8.5. Snow cover depth might be close to 0 cm for both RCP2.6 and RCP8.5 scenarios. Regarding frozen water in soil, it was detected that for RCP2.6 it might be around 2.5 cm and close to 0 cm for RCP8.5. For soil moisture it was found that during JFMAM it might increase to around 52 cm in case of RCP2.6 and it might be less for RCP8.5, around 46 cm.

4.2.3 Analysis of data representing the third period, 2071–2100

The analysis of climate model data representing RCP2.6 showed that averaged soil temperature might range from 0 to +5 ^{o}C in southern Sweden (figure 7, first row). In contrast to the optimistic RCP2.6 scenario, climate model data representing RCP8.5 showed soil temperature increase up to 5-7 ^{o}C by 2100 (figure 7, second row). Under RCP4.5 scenario soil temperature range might be 3-5 ^{o}C (figure 16, Appendix).

The snow cover maps (figure 8) for the last period of the century showed that the snow cover depth could decrease dramatically under all tree RCP scenarios. In southern parts there could be almost no snow cover averaged during entire study season. In central and northern parts snow cover depth could range 8-20 cm for RCP2.6 and 2-7 cm for RCP8.5.

Average frozen water in soil (figure 9) for the period 2071–2100 showed visible decrease of frozen water depth in soil in the entire region. Focusing in the southern part, the depth could be around 10 cm for RCP2.6, whereas under RCP8.5 scenario the depth might be close to 0 cm by the end of the century.

The average soil water depth during ONV and JFMAM (figures 10, 11) showed that it could range from 39 to 42 cm for the pessimistic RCP2.6 scenario, and from 38 to 41 cm for the pessimistic RCP8.5 scenario, in southern Sweden. In case of RCP 4.5 scenario the range of soil water depth might range from 42 to 44 cm (figures 19, 20, Appendix).

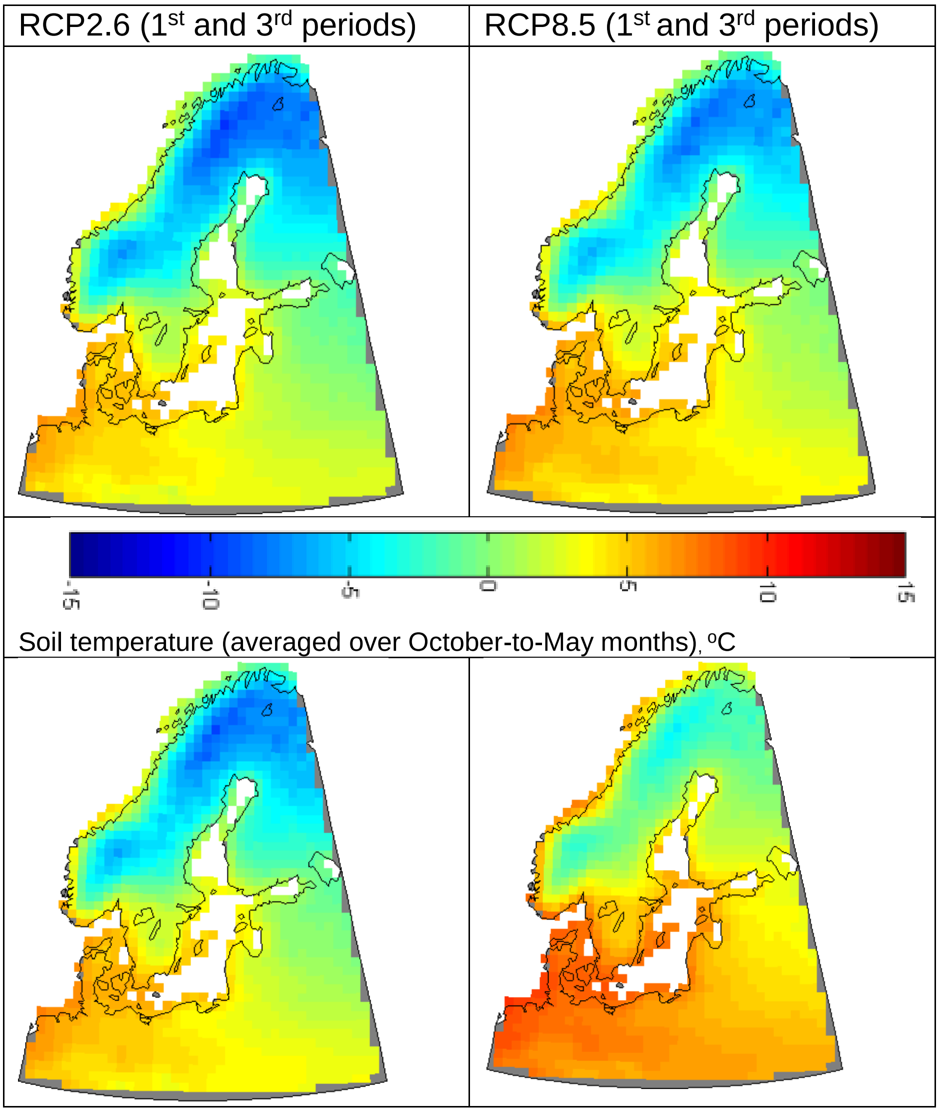

Figure 7. Soil temperature (ºC) during entire study season (October 1 to May 31) according to climate model data representing two future scenarios - RCP 2.6 and 8.5. The maps in the upper row show average results for the period 2011-2040, the maps in the second row show average results for the period 2071-2100.

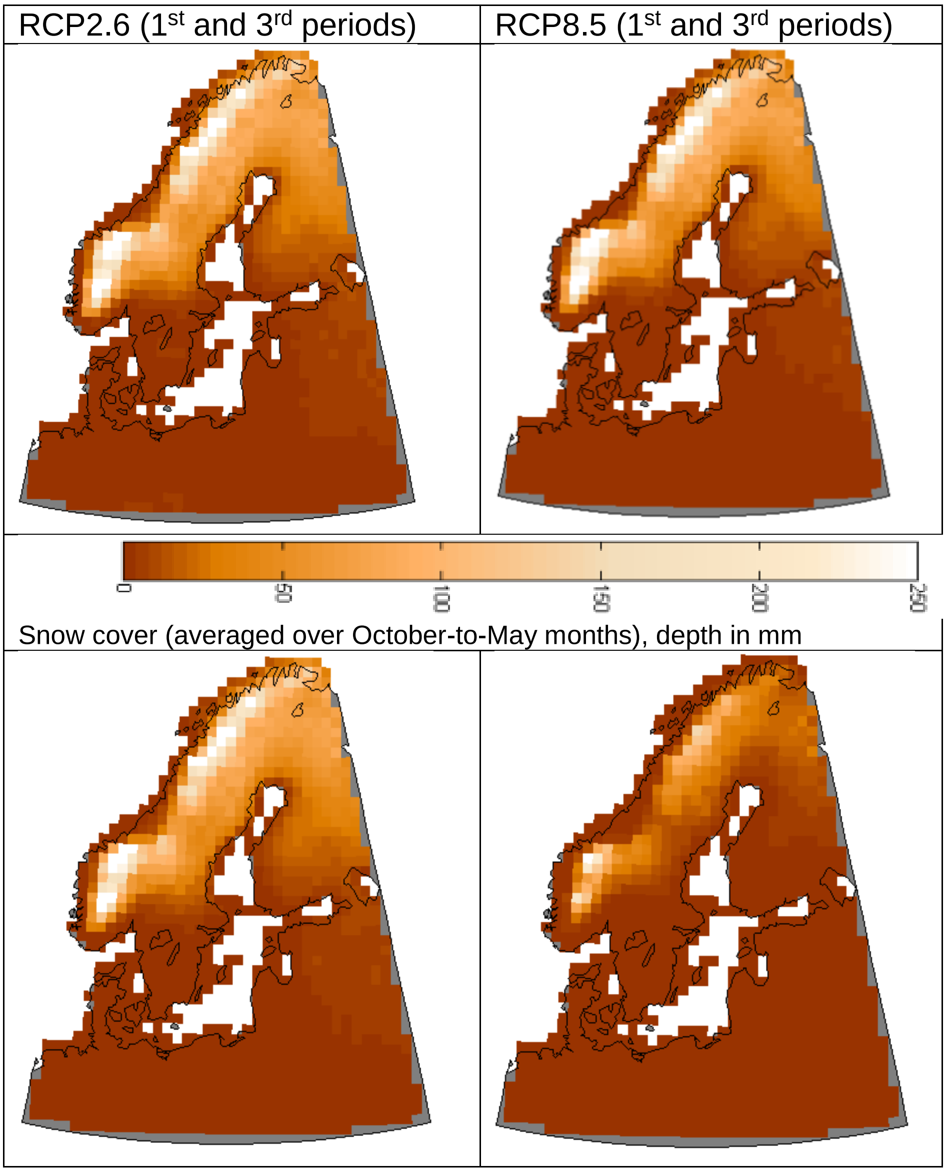

Figure 8. Snow cover (depth in mm) during entire study season (October 1 to May 31) according to climate model data representing two future scenarios - RCP 2.6 and 8.5. The maps in the upper row show average results for the period 2011-2040, the maps in the second row show average results for the period 2071-2100.

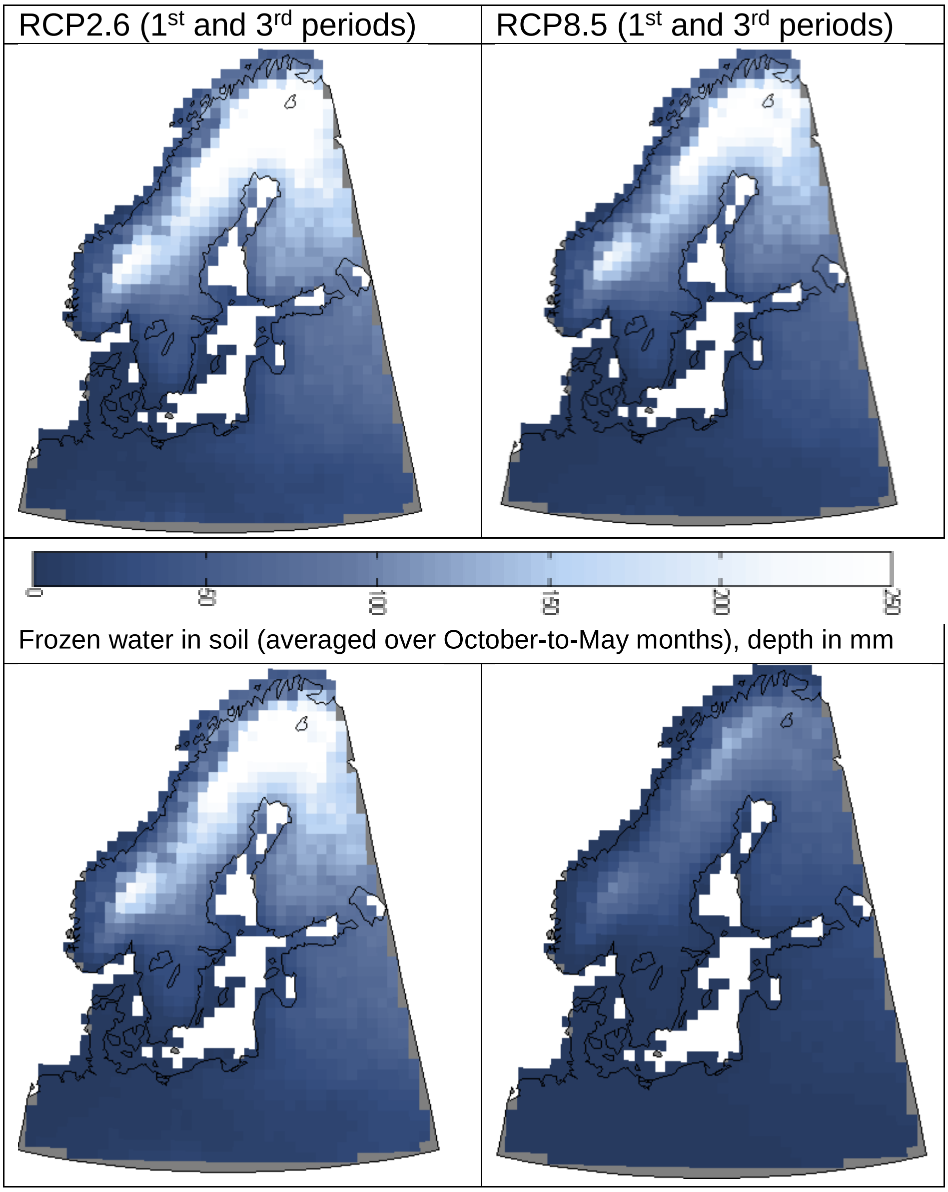

Figure 9. Frozen water in soil (depth in mm) during entire study season (October 1 to May 31) according to climate model data representing two future scenarios - RCP 2.6 and RCP8.5. The maps in the upper row show average results for the period 2011-2040, the maps in the second row show average results for the period 2071-2100.

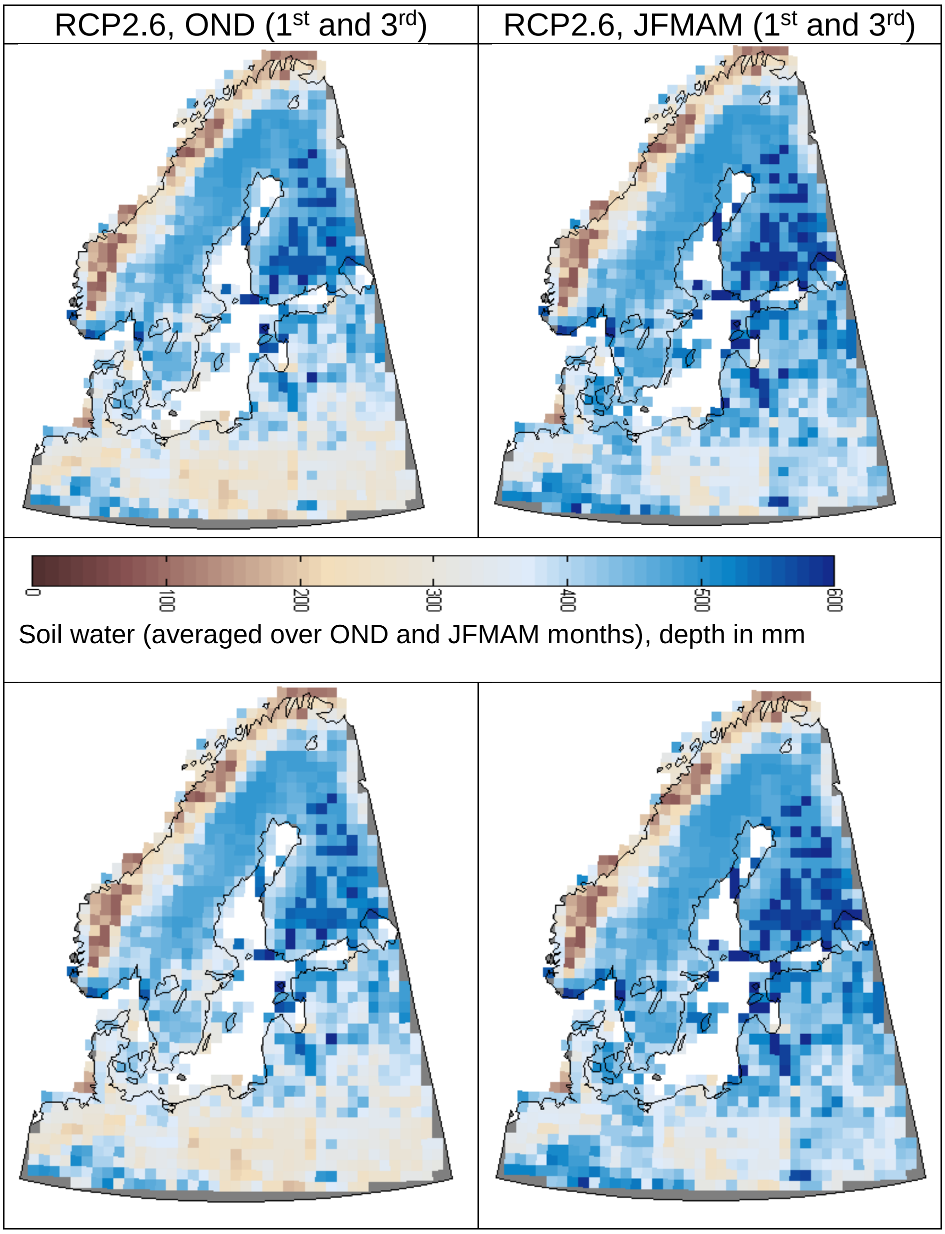

Figure 10. Soil water (depth in mm) according to climate model data representing RCP2.6 scenario. The maps in the upper row show average results for the period 2011-2040, and the maps in the second row show average results for the period 2071-2100.

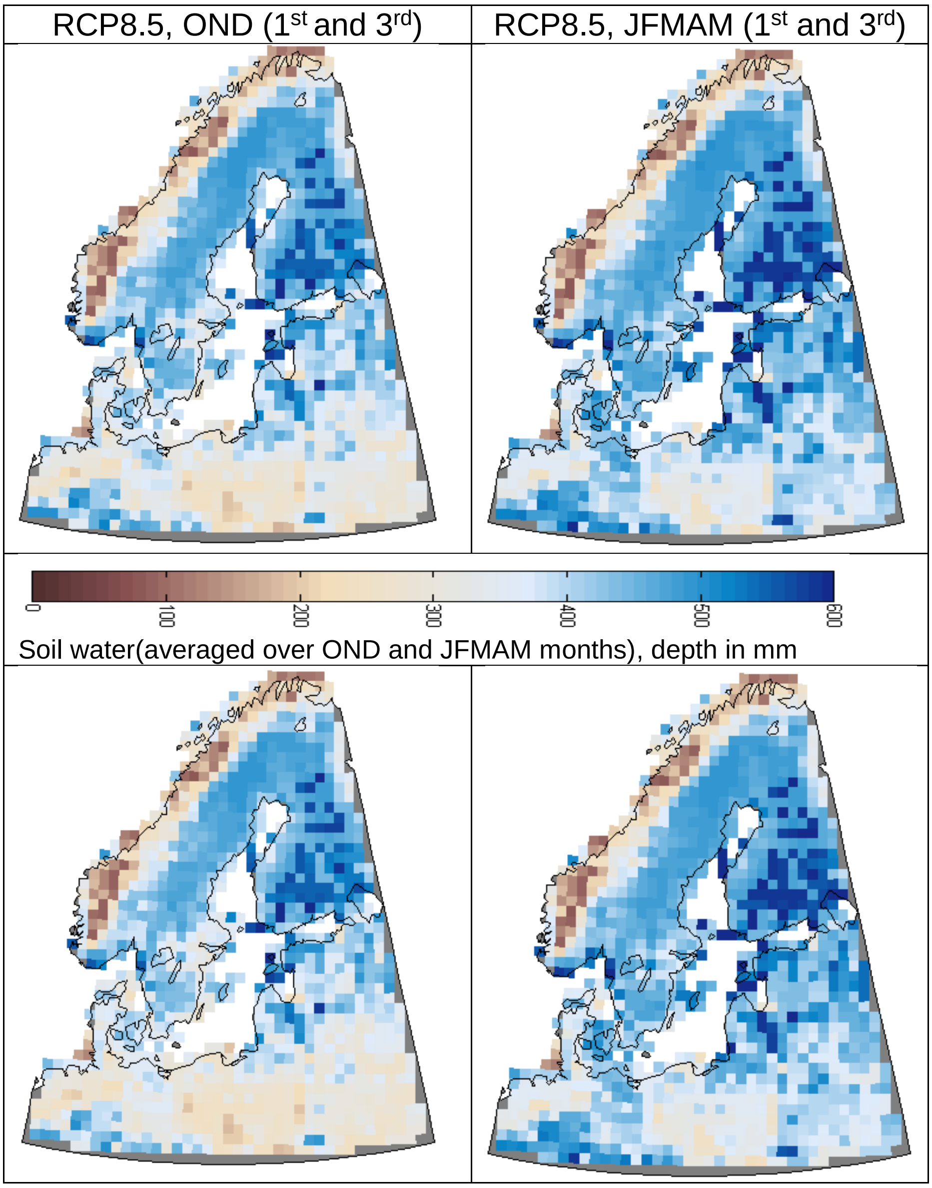

Figure 11. Soil water (depth in cm) according to climate model data representing RCP8.5 scenario. The maps in the upper row show average results for the period 2011-2040, the maps in the second row show average results for the period 2071-2100.

4.3 Comparison of soil conditions given RCP2.6 and RCP8.5

The figures 7 to 11 show that the inter-annual variations of temperatures, snow cover, content of frozen water in soil, soil moisture depths are considerably different for RCP2.6 and RCP8.5 scenarios, also varying between the JFMAM and OND seasons.

4.3.1 Soil conditions during October-to-December season

Focusing on more striking features, shown in the figure 12 (first column), it can be seen that the mean soil temperature in the first period was projected to be 3.5 ^{o}C in the first period and increased to 4 ^{o}C in the second period for RCP2.6. In contrast, RCP8.5 scenario it was around 4 ^{o}C in the first period and raised up to 6.3 ^{o}C by the end of the century.

The mean depth of snow cover for RCP2.6 (figure 12, second column) was projected to increase slightly from around 0 (first period) to 3 cm (third period). The results of climate data representing RCP8.5 for the last period showed that the snow cover in southern Sweden could become close to 0 cm.

According to the climate model data, the mean depth of frozen water in soil was the highest, i.e. 10cm in the first 30 years for RCP2.6 scenario (figure 13, first column). Model projections indicate a decrease by 5 cm by the end of the century. Results were similar for RCP8.5 - mean depth of frozen water could decrease by 4cm (from 6cm), reaching to 2cm by the end of the century. Comparing the means and variations of soil moisture depth (figure 13, second column), it was noticed that climate model data representing RCP2.6 the depth for the first period was 1.5 cm which then decreased reaching to 40 cm, and for RCP8.5 the depth decrease from 41 to 40 cm from first to third period of the century.

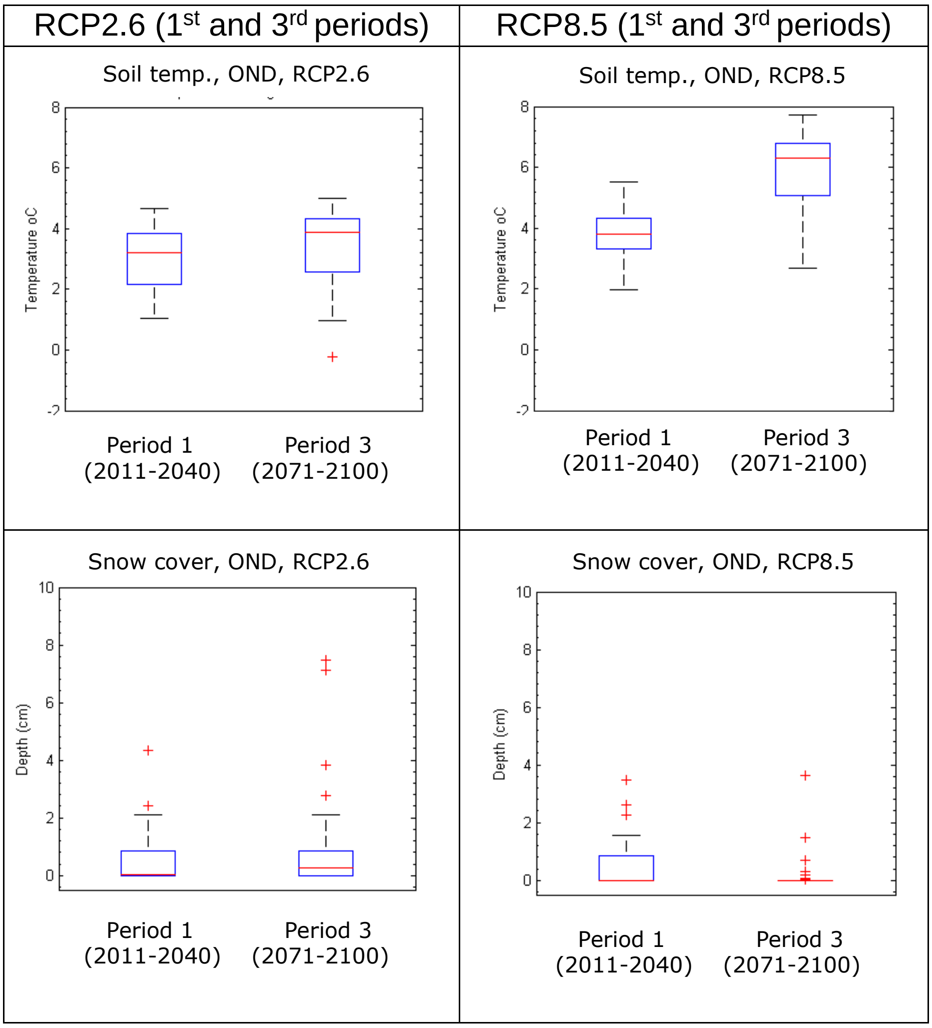

Figure 12. Results of the analysis of soil temperature (ºC) and snow cover depth (cm) for OND (October-November-December). First column shows the results representing RCP2.6, and the second column shows the results for the RCP8.5. The red line within the box denotes the median, the box gives the upper and lower quartile, which contains 50% of the data. The upper and lower whiskers give the maximum and minimum of the distribution within the range of 1.5 times the interquartile distance from the median. Outliers are marked with the red crosses.

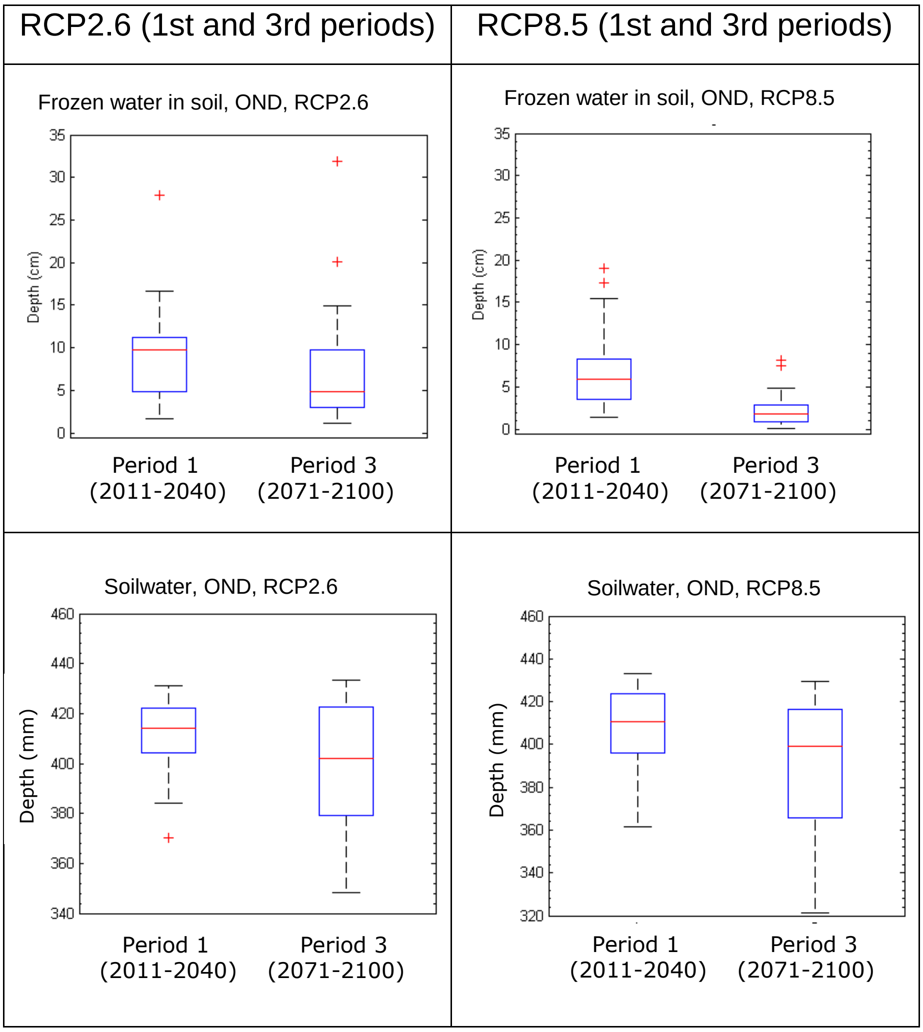

Figure 13. Results of the analysis of depth of frozen water in soil (cm) and soil water depth (mm) for OND (October-November-December). First column shows the analysis of climate model data representing RCP2.6, and the second column shows the analysis of climate model data representing RCP8.5.
The red line within the box denotes the median, the box gives the upper and lower quartile, which contains 50% of the data. The upper and lower whiskers give the maximum and minimum of the distribution within the range of 1.5 times the interquartile distance from the median. Outliers are marked with the red crosses.

4.3.2 Soil condition during January-to-May season

Boxplots of four parameters for the JFMAM season under the RCP2.6 and RCP8.5 scenarios showed the following:

The soil temperatures are relatively low in JFMAM compared to OND (figure 14, first column). Soil temperature was lower in case of RCP2.6 scenario than RCP8.5. Focusing on the more significant differences of climate data representing RCP2.6 it can be seen that the mean soil temperature was 1.5 ^{o}C during first period (2011-2040), and close to 3 ^{o}C in third period (2071-2100). For RCP8.5 mean soil temperature was 2.2 ^{o}C in the first period and reached to 5.5 ^{o}C by the end of the century.

The mean of snow cover depth by the year 2040 for RCP2.6 was 2.6 cm, and the variability ranged from 1 to 6.5 cm (figure 14, second column). The mean was close to 2.5 cm in the last three decades. For the RCP8.5 scenario the mean for the first period was 1.8 cm which might then decrease dramatically reaching to almost 0 cm by 2100, and the variability might range from 0 to 1 cm.

Frozen water depths in soil for JFMAM period showed visible differences compared with those for the OND (figure 15, first column). In the first period of twenty-first century (2011-2040) the means of frozen water depth in soil was 61 and 38 cm for RCP2.6 and RCP8.5 scenarios respectively. In the last period (2071-2100) frozen water depth in soil decreased to 45 cm for RCP2.6, while for the pessimistic RCP8.5 scenario it decreased significantly reaching to 2 cm.

The analysis of climate model data for soil water depth (figure 15, second column) showed that its mean was around 41 cm during the first period and around 40 cm during the third period of the twenty-first century for both scenarios. The variability was largest for RCP8.5 in the third period, ranging from around 41 to 42 cm.

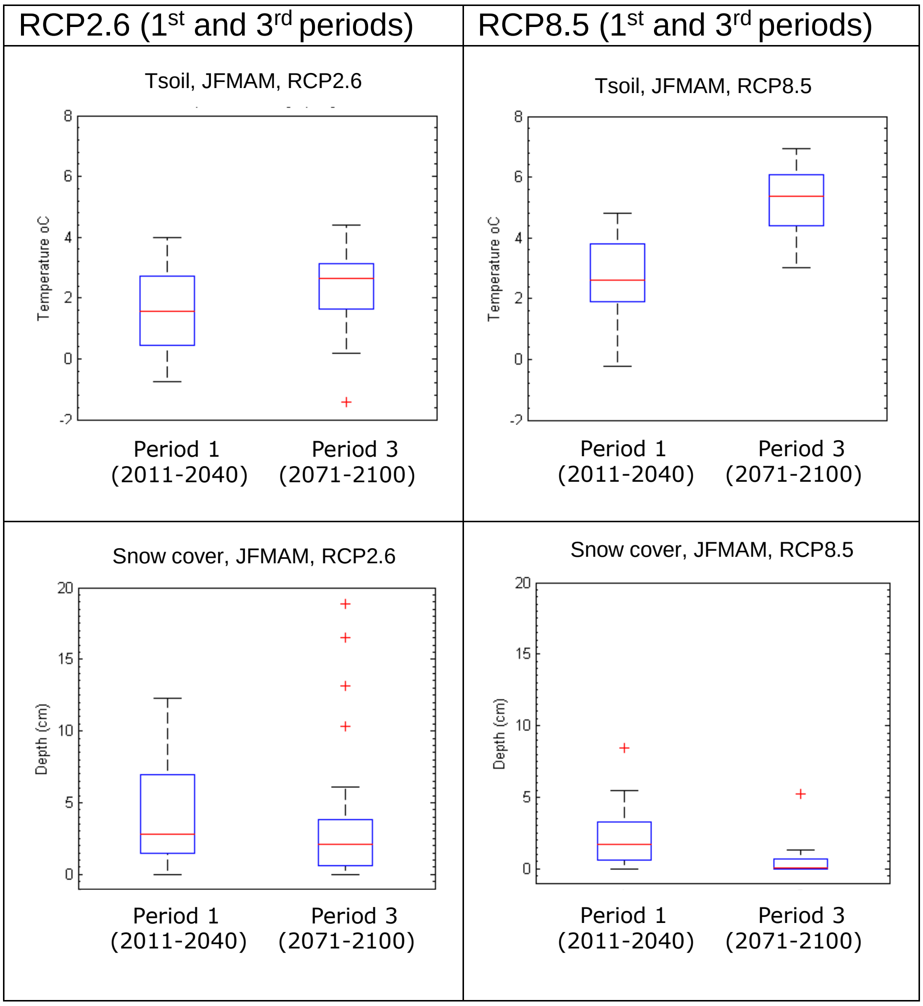

Figure 14. Results of the analysis of soil temperature (ºC) and snow cover depth (cm) for OND (October to December). First column shows the analysis of climate model data representing RCP2.6, and the second column shows the analysis of climate model data representing RCP8.5.
The red line within the box denotes the median, the box gives the upper and lower quartile, which contains 50% of the data. The upper and lower whiskers give the maximum and minimum of the distribution within the range of 1.5 times the interquartile distance from the median. Outliers are marked with the red crosses.

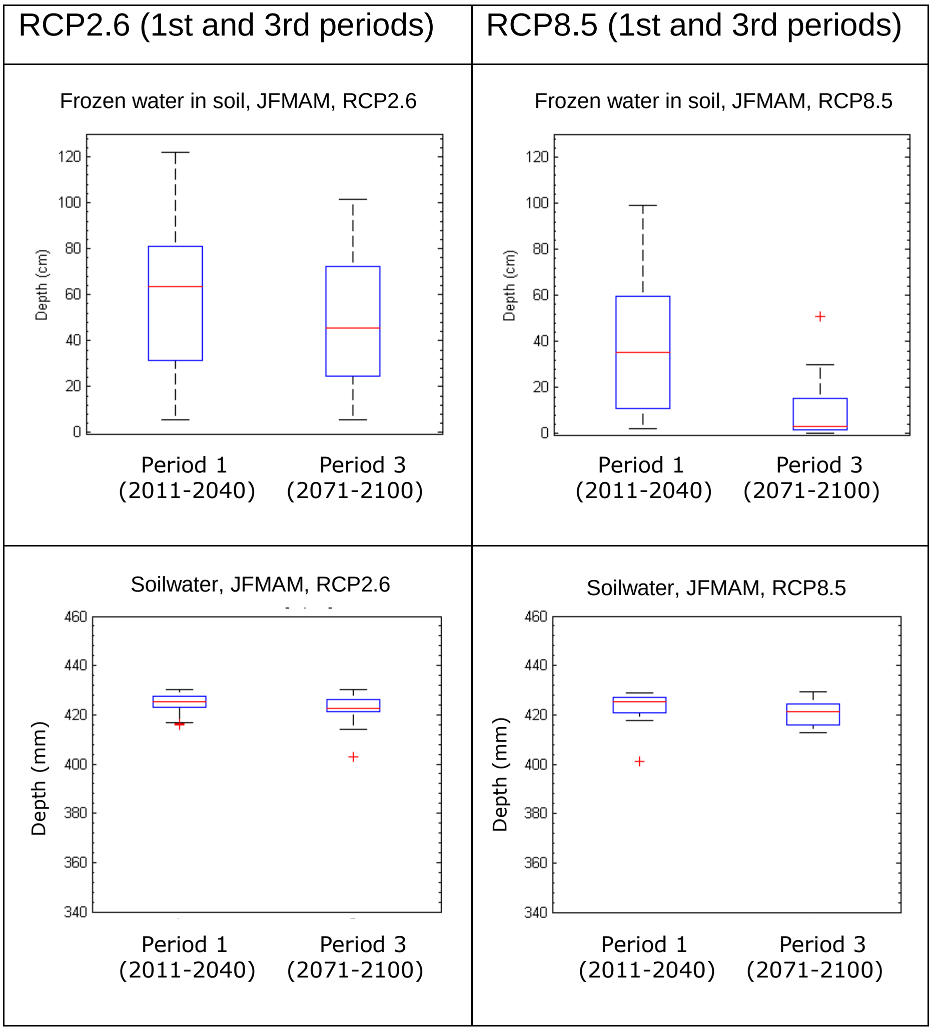

Figure 15. Results of the analysis of depth of frozen water in soil (cm) and soil water depth (mm) for OND (October to December). First column shows the analysis of climate model data representing RCP2.6, and the second column shows the analysis of climate model data representing RCP8.5.
The red line within the box denotes the median, the box gives the upper and lower quartile, which contains 50% of the data. The upper and lower whiskers give the maximum and minimum of the distribution within the range of 1.5 times the interquartile distance from the median. Outliers are marked with the red crosses.

Chapter 5

5. Discussions

The changing climate has impact on water and temperature conditions of forest soils. When analysing the historical storm damage data by Nilsson (2008) and Nilsson et al. (2004) (figure 3), it can be seen that the highest number of damages mostly occurred in September-to-December season. In her research Nilsson (2008) also found that the highest damage was recorded in the southern Sweden throughout the period of 1954-2007. The analysis of current work (figure 6) showed that in OND the level of soil moisture was 10 cm higher than in JFMAM, and there was 6 cm less frozen soil in OND than in JFMAM season. This indicates that storm damage in Sweden happened mostly when the ground was more wet and less frozen. In those conditions trees were more vulnerable to the wind throw.

Research efforts were conducted to analyse and assess the windiness in the region and throughout the country in the past. It was indicated by Achberger et al. (2006) that wind flow conditions were stronger and more coherent in space in southern Sweden than in central and northern Sweden. In their work Bengtsson and Nilsson (2007) showed that recorded forest storm damage has significantly increased since the beginning of the last century. The authors mention, that those drastic events could be the signs of changing climate. However, it is difficult to say, and that the increase in storm felling is attributed to a higher standing volume of forests today than 100 years ago (Nilsson et al., 2004).

A research conducted by (Usbeck et al., 2010) on forest damage caused by wind storms in Switzerland's showed similar trend as some previous research for Sweden. The authors found that severe storm damage in Switzerland in the last century occurred almost always when soils were unfrozen (96 %) and more wet (96%). The authors concluded that increased storm damage in forests in Switzerland in the 20th century were associated with warm winter temperature, high precipitation, and increasing maximum gust wind speed.

Considering studies, which indicate increase in the frequency and strength of winds, and studies, indicating increase in precipitation and temperature, wind throw might become more frequent and might cause higher damage to forests. Work by Blennow and Olofsson (2008) for north and south of Sweden, showed that throughout the twenty-first century the sensitivity of forests to wind and the probability of wind damage could increase, being higher in south than in north. Similar studies were conducted for the region and other countries which showed similar tendencies. For example, in a study conducted for Germany (Panferov et al., 2009) it was indicated that increased storm damage in forest was due to increasing maximum wind speeds, precipitation and soil water contents.

As for the future projections for the region and Sweden in particular, small increases in extreme wind speed were projected for Central and Northern Europe for winter periods (Rauthe et al., 2010; Rockel and Woth, 2007; Schwierz et al., 2010). In particular, research conducted for Finland (Peltola et al., 1999) projected that soil frost period could decrease from 4–5 months to 2–3 months per year in southern Finland. Moreover, they found that by the end of the century the proportion of severe winds might increase from present 55% to 80% in southern Finland.

In current study analyses for future soil conditions was conducted as well, in order to detect possible damage that can be caused to forests in the future. The results of current work showed that average soil temperature during October-May could increase by 1.5 and 3.5 cm for RCP2.6 and RCP8.5 respectively (figure 7). This analysis correspond well to projections by Swedish regional climate modelling programme SWECLIM (Mellander et al., 2007) which was conducted under 2 different scenarios. The model projected increase in the average soil temperature by 0.9 –1.5°C, advance soil warming by 15 –19 days in spring and increased soil freeze–thaw cycles by 31 – 38%.

Previous studies related to future changes in snow cover in the region, used different models and different scenarios and they projected that: 1) the largest absolute changes of snow cover might occur in the northern Baltic Sea area, on the western slope of the Scandinavian mountains (Jylhä et al., 2008); 2) the period of persistent snow pack could decrease by 73 – 93 days and there could be more days with only a thin snow cover (Mellander et al., 2007). In current work, when analysing the future changes in snow cover (figure 8), similar results were found. In particular, it was found that snow cover could decrease considerably, reaching to 0 cm in the south during OND season under RCP8.5 scenario by the end of the century. In contrast, climate data set representing RCP2.6 showed snow cover increase from 0 cm (2011-2040) to around 3 cm during the third decade of the century. This can be explained by the positive mitigation changes to be taken under RCP2.6 (IPCC, 2013b).

Analyses of current work showed that soil water mean could increase in southern Sweden especially during the last period of the century (2071-2100) under RCP8.5, (figures 10, 11). The same trend was observed also for the central and northern parts of Sweden, but with moderate variations. Results of this thesis agree well with the projections of Räisänen and Joelsson (2001). According to their work in the warming climate winter precipitation could more likely fall as rain in northern and central Europe which would lead to more wet soils and accordingly more damage by increased wind speeds.

In conditions, when there is less snow fall and more rainfall in autumn, lack of frozen ground and increased soil moisture makes forest stands more susceptible to wind throw. Forest machinery used for clear cutting and thinning, is another factor causing damage to trees' roots, especially when the ground is unfrozen and wet. The decrease of ground frost complicates forestry work and harvesting on wet soil conditions leads to more damage of forestry sites. The results of current study indicate that with a temperature rise, there might be more damage in the future. Especially forests in southern Sweden could become even more vulnerable to human and climate induced damages.

However, forests are complex systems and understanding of the processes and response to climatic changes requires integration of multiple disciplines. Apart from soil temperature, soil moisture, ground frost and wind throw, causing damage to forest stands, there are number of factors which can either enhance or reduce the vulnerability of trees. Susceptibility of trees to wind damage depends on factors, such as trees' anchorage capacity, soil science (e.g. soil physical, mechanical and chemical properties), meteorology, and climatology. Critical wind speed is an important aspect to be considered since in different wind damage models it varies. Several other predisposing factors, such as tree height, stem taper (ratio of diameter at breast height to tree height), stand density, tree species also determine the critical wind speed at which damage might occur (Lohmander and Helles, 1987; Nykänen et al., 1997; Valinger et al., 1993). These factors were left out from current work as they were considered of less importance and hard to quantify at the scale of this study.

Thorough research on the risk of damage under both present and future climatic conditions is needed for successful forest management. For example, by changing the heavy machines into lighter machinery could minimize the driving damage to the trees during the timber harvesting and clear cutting. Another important aspect is to consider the specific ability of tree species for acclimatization and adaptation by natural selection. By planting tree species, which are more climate adaptive and resilient to changes in soil temperature, soil moisture, ground frost, and wind speeds, the risk of damage can be reduced. Forest owners and other land managers must be aware of the potential forest damages, directly or indirectly influenced by the changing climate. Cooperation between forest owners and scientists plays an important role in adaptation and mitigation actions and can improve management of the forestry and contribute to adaptation strategies of forestry in Sweden.

Chapter 6

6. Conclusions

The model analysis of four forest soils parameters (soil temperature, snow cover, soil water and frozen soil) showed that:

- during the last century, damages by severe storm events took place in the times, when the depth of frozen soil was low and the soil moisture was high;
- by the year 2100, due to warming climate soil temperature might increase in the country, in particular in southern Sweden, under all tree RCP scenarios during October-May season, being the highest for the RCP8.5;
- snow cover might decrease substantially under all RCPs, reaching to 0 cm in southern Sweden by the end of the twenty-first century under all tree RCP scenarios;
- changes of snow cover regimes might lead to decrease of frozen soil depth and increase of soil water depth especially during JFMAM season;
- these climate induced changes might negatively influence on tree resilience against severe storm events in the future;
- under the changing climate decreased frozen water in soil, increased soil moisture can lead to more tree root damage caused by increased wind speeds, clear cutting and tinning by heavy machinery.
- Overall, the resilience of trees against climate and human induced damages have been, and might continue to be endangered.

Chapter 7

7. Recommendations and future work

There were several limitations during this work and future work is required in order to improve the results.

- It is important to do analysis of seasonal variations of four variables (soil temperature, snow cover, soil moisture and frozen water in soil) by choosing shorter periods of study (e.g. autumn, winter, spring), in order to detect more specific relationships between changes in climatic conditions and soil characteristics.
- Integration of other factors into research is essential for receiving more probabilistic results. Thorough research, related to soil physical, mechanical chemical properties; meteorology; climatology; tree height, stand density, stem taper and climate resilience capabilities of different tree species is vital for understanding resilience capabilities of trees under changing climate.
- Comparison of different modelling results (under the same scenarios) for the region is needed for comparing the results of this work, and for more probabilistic forecasts of the state of the forest soils in the changing climate.

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Appendix

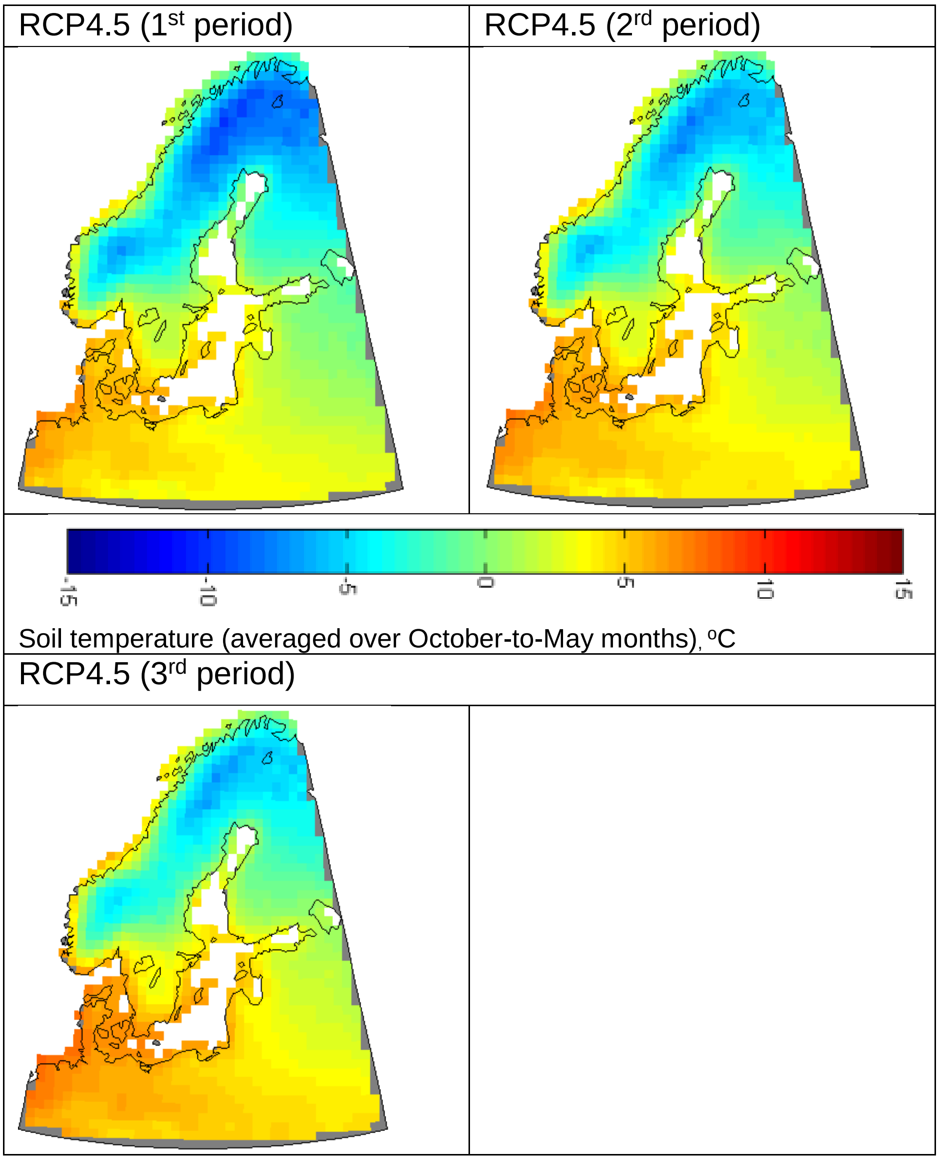

Figure 16. Soil temperature (ºC) according to climate model data representing RCP4.5 future scenario for the entire study season (October 1 to May 31) according to climate model data representing. The map in the left upper corner shows average results for the period 2011-2040, the map in the right upper corner shows average results for the period 2041-2070, and the map in the second row shows average results for the period 2071-2100.

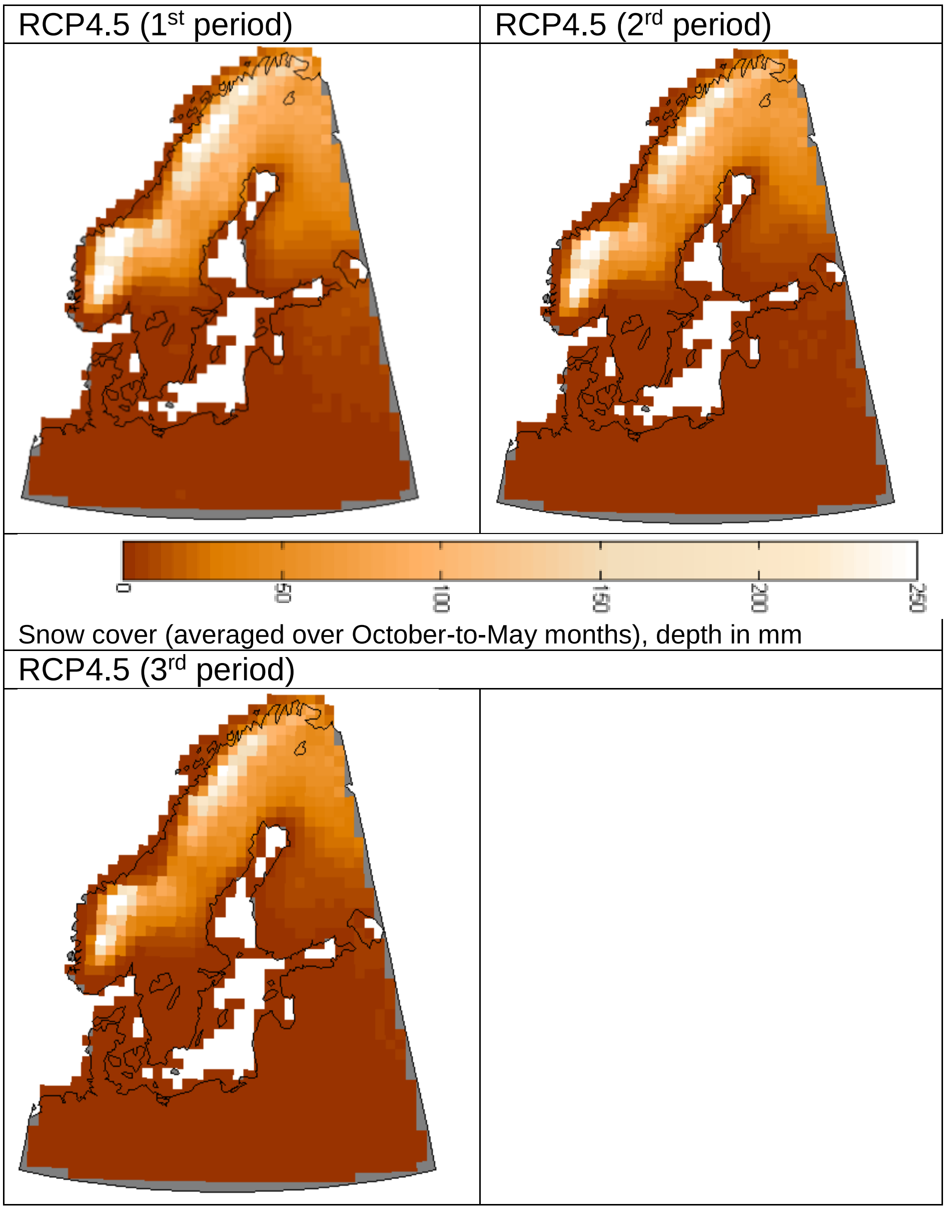

Figure 17. Snow cover (depth in mm) according to climate model data representing RCP4.5 future scenario for the entire study season (October 1 to May 31) according to climate model data representing. The map in the left upper corner shows average results for the period 2011-2040, the map in the right upper corner shows average results for the period 2041-2070, and the map in the second row shows average results for the period 2071-2100.

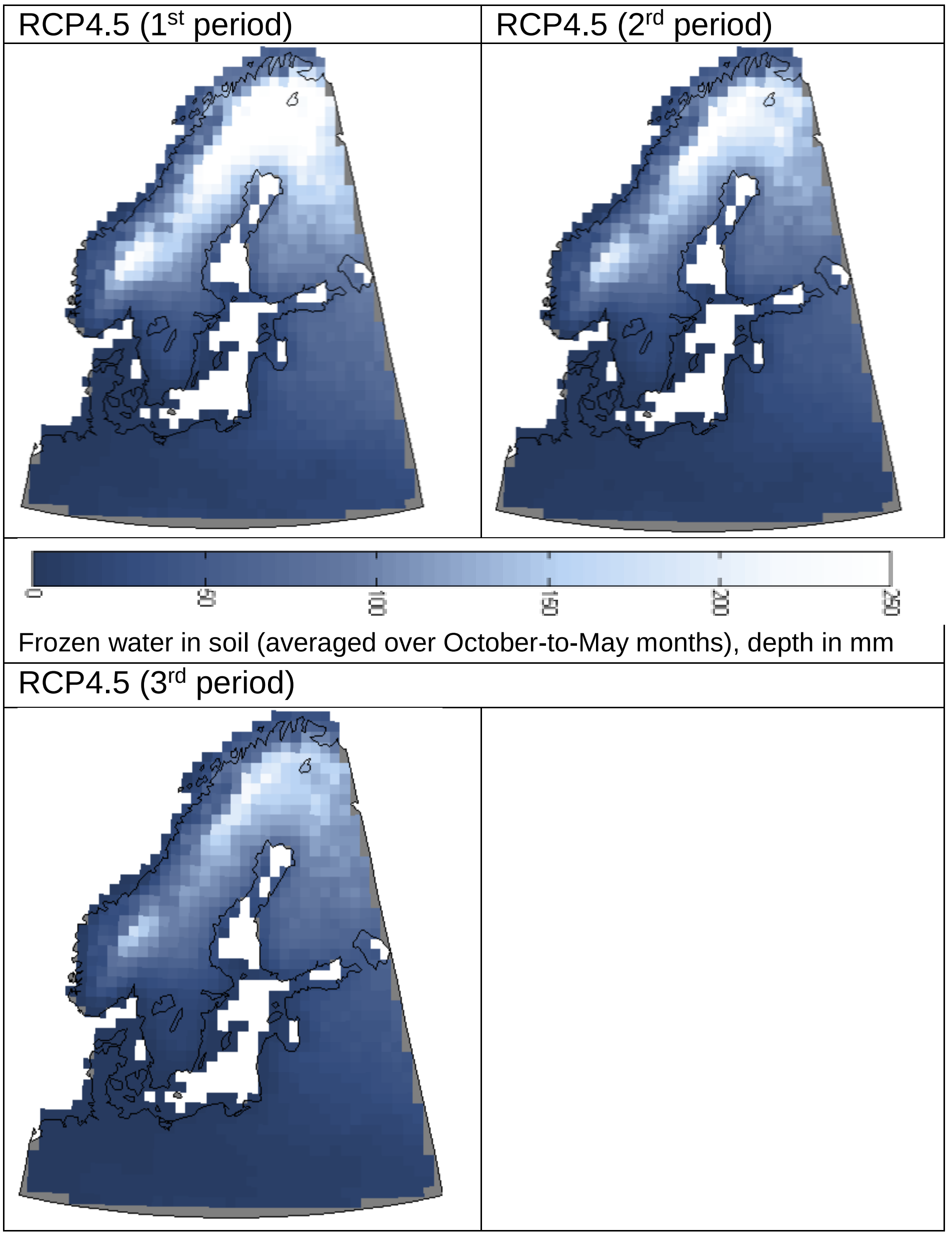

Figure 18. Frozen water in soil (depth in mm) according to climate model data representing RCP4.5 future scenario for the entire study season (October 1 to May 31) according to climate model data representing. The map in the left upper corner shows average results for the period 2011-2040, the map in the right upper corner shows average results for the period 2041-2070, and the map in the second row shows average results for the period 2071-2100.

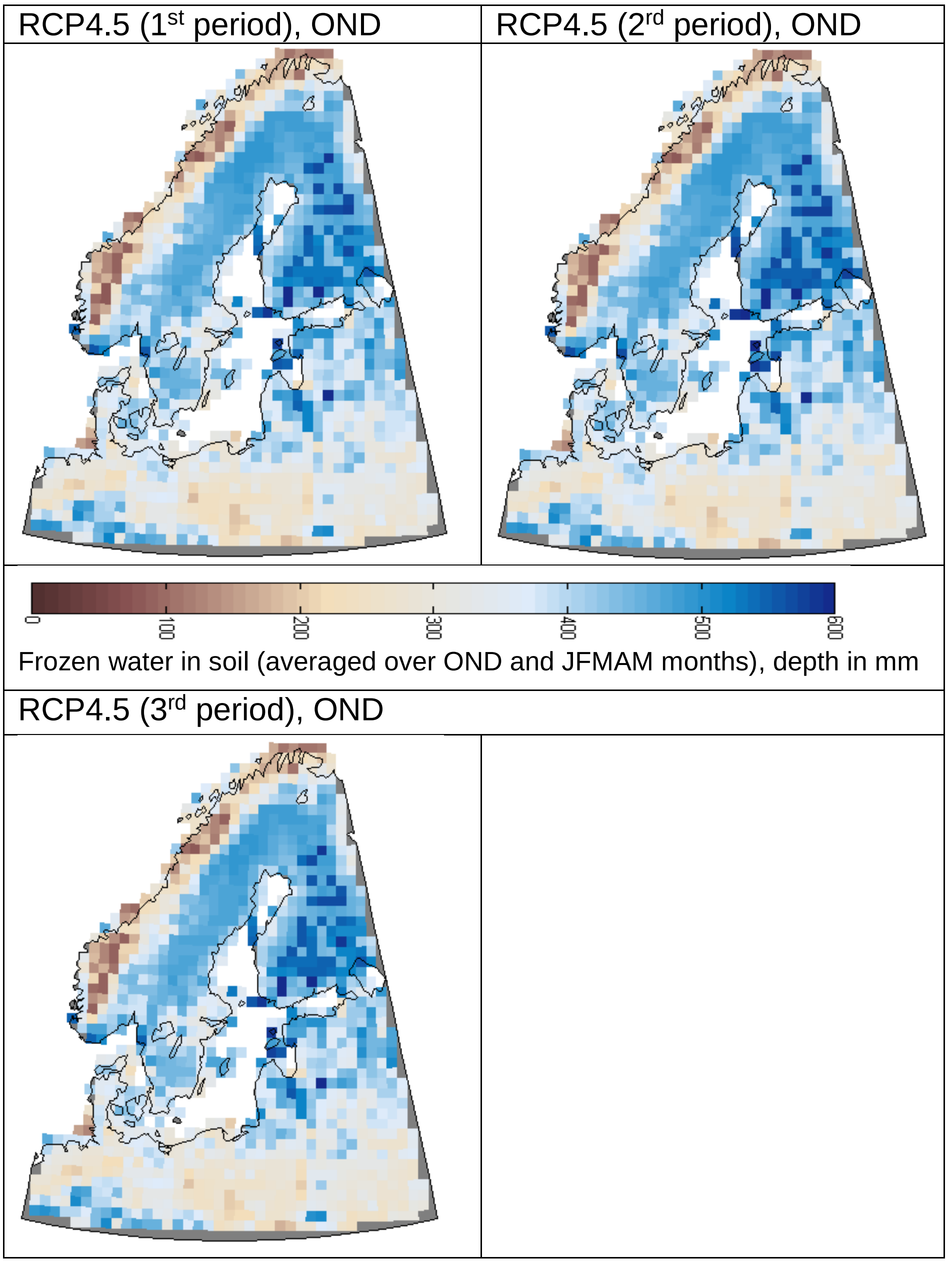

Figure 19. Soil water (depth in mm) according to climate model data representing RCP4.5 future scenario, for the October-November-December (OND) season. The map in the left upper corner shows average results for the period 2011-2040, the map in the right upper corner shows average results for the period 2041-2070, and the map in the second row shows average results for the period 2071-2100.

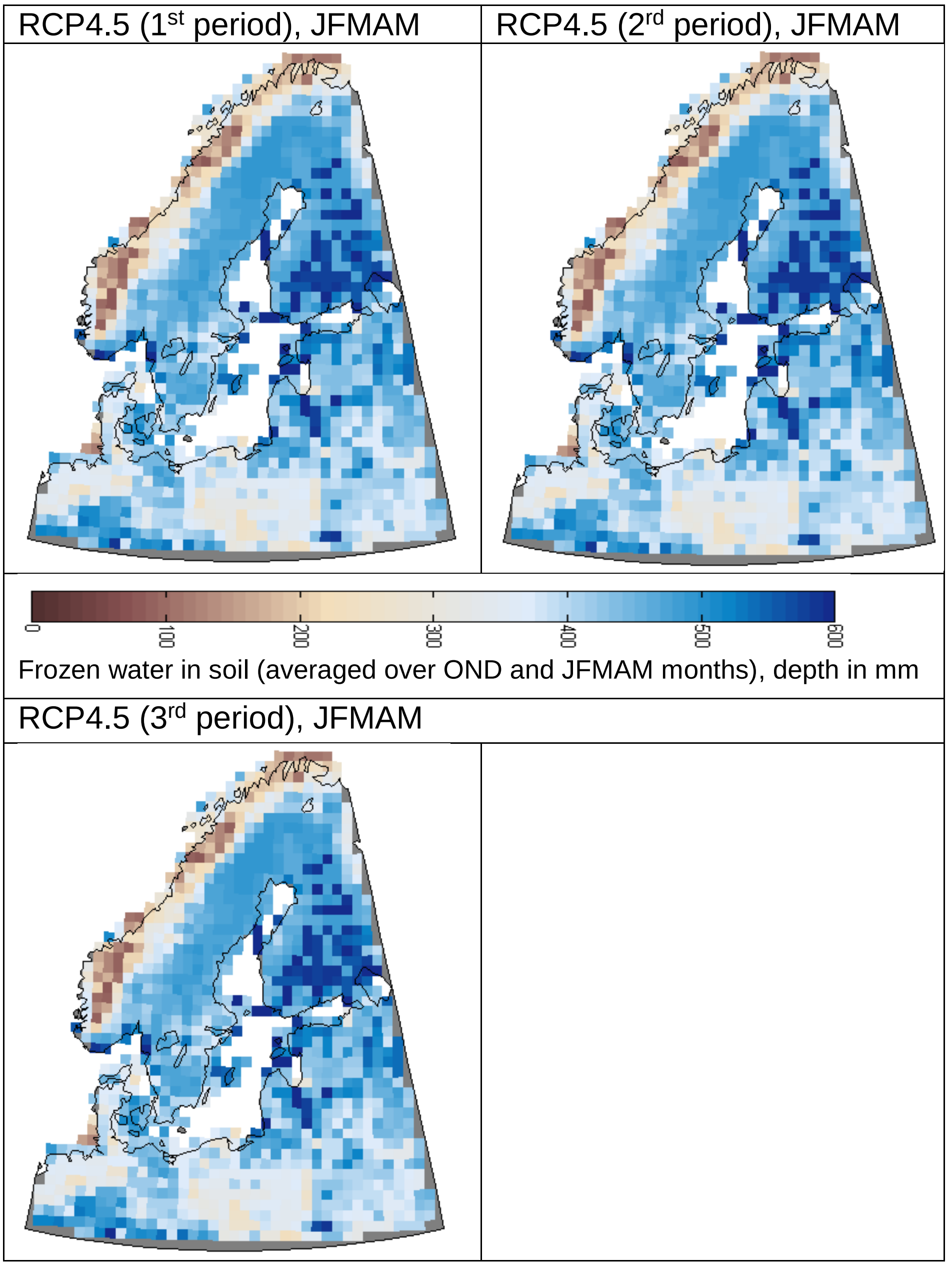

Figure 20. Soil water (depth in mm) according to climate model data representing RCP4.5 future scenario, for the January-February-March-April-May (JFMAM) season. The map in the left upper corner shows average results for the period 2011-2040, the map in the right upper corner shows average results for the period 2041-2070, and the map in the second row shows average results for the period 2071-2100.

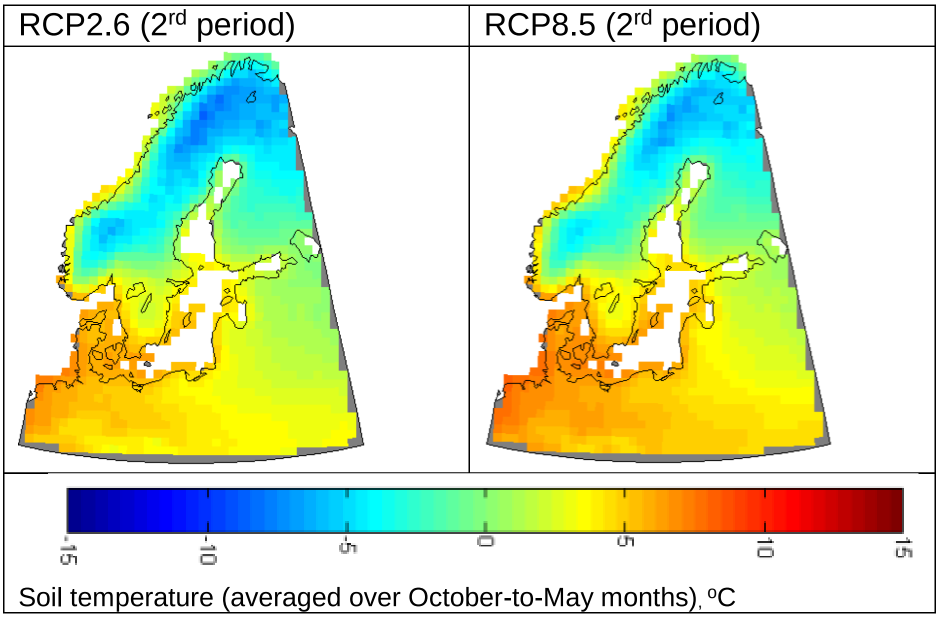

Figure 21. Soil temperature (ºC) for the entire study season (October 1 to May 31) according to climate model data representing two future scenarios during the second period (2041-2070). The map in the left shows average result for RCP2.6, and the map on the right shows average result for RCP8.5.

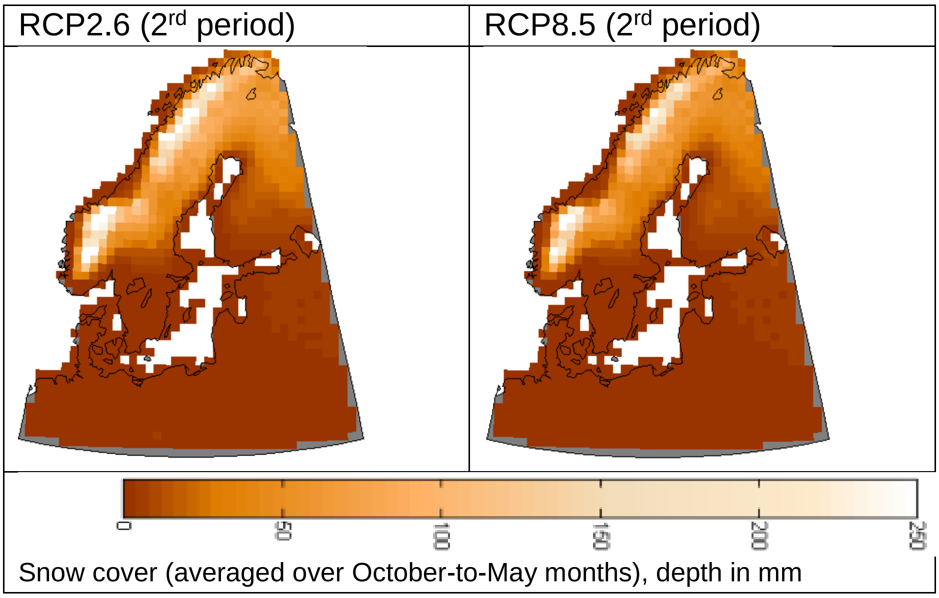

Figure 22. Snow cover (depth in mm) for the entire study season (October 1 to May 31) according to climate model data representing two future scenarios during the second period (2041-2070).The map in the left shows average result for RCP2.6, and the map on the right shows average result for RCP8.5.

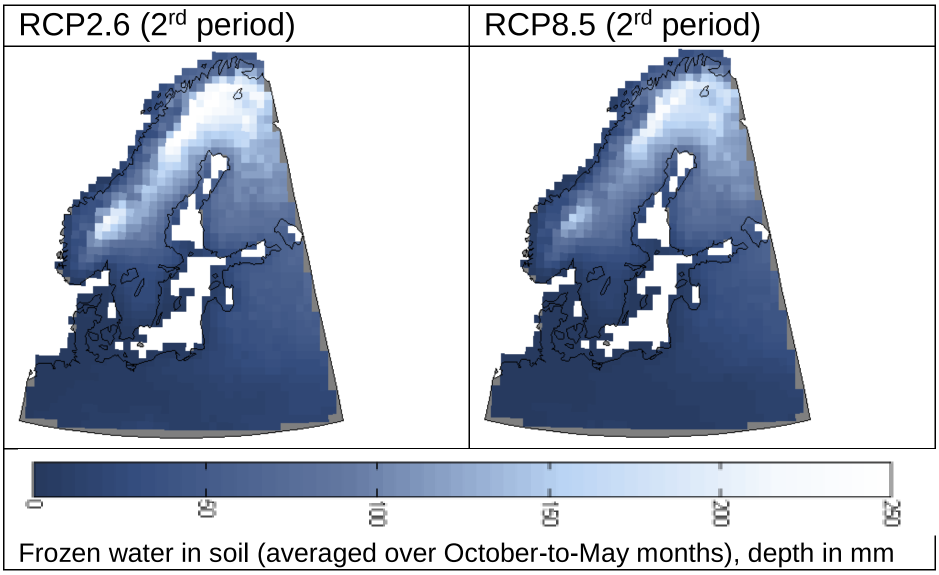

Figure 23. Frozen water in soil (depth in mm) for the entire study season (October 1 to May 31) according to climate model data representing two future scenarios during the second period (2041-2070).The map in the left shows average result for RCP2.6, and the map on the right shows average result for RCP8.5.

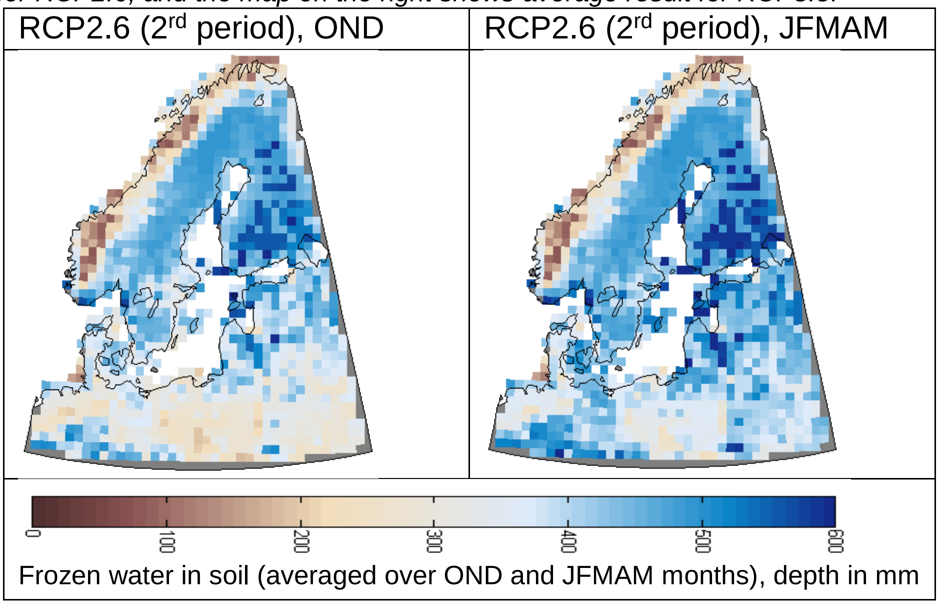

Figure 24. Soil water (depth in mm) according to climate model data representing RCP2.6 future scenario, for the second period (2041-2070). The map in the left shows average result for October-November-December (OND), and the map on the right shows average result for January-February-March-April-May (JFMAM) season.

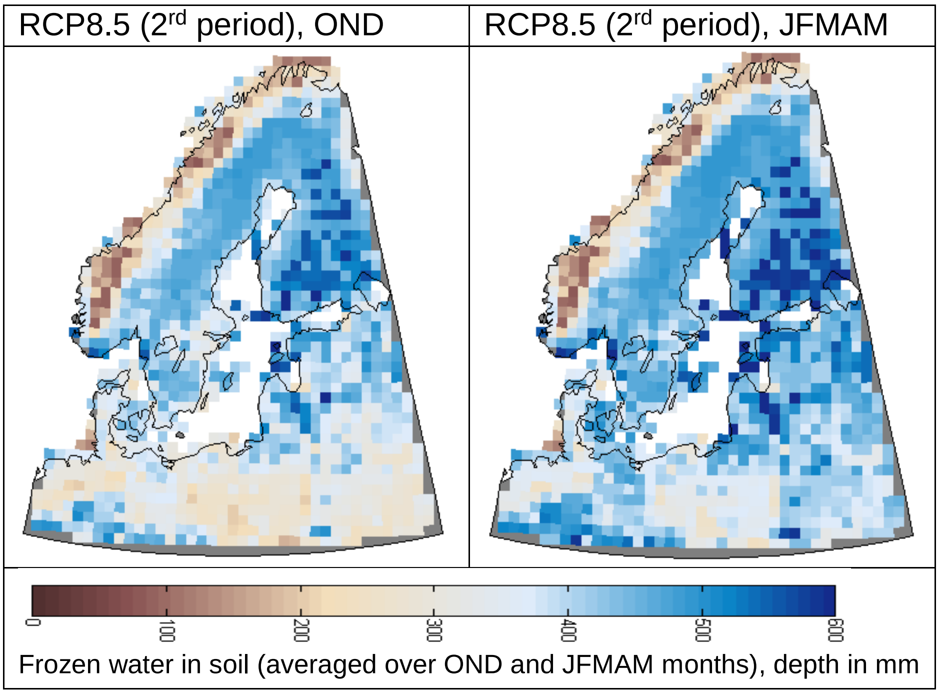

Figure 25. Soil water (depth in mm) according to climate model data representing RCP8.5 future scenario, for the second period (2041-2070). The map in the left shows average result for October-November-December (OND), and the map on the right shows average result for January-February-March-April-May (JFMAM) season.

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