

Impact of climate change on soil frost under snow cover in a forested landscape

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ABSTRACT: This study was aimed at assessing the potential impacts of climate change on the depth and duration of soil frost under snow cover in forests growing at different geographical locations in Finland. Frost simulations using a process-based forest ecosystem model (FinnFor) were made for Scots pine *Pinus sylvestris* L. stands (height 17 m, stand density 1100 stems ha⁻¹) growing on a moraine sandy soil. The climate change forecast used in the computations was based on the global ocean-atmosphere general circulation model HadCM2 that was dynamically downscaled to the regional level. The simulated climate warming during the winter months was about 4 to 5°C by the end of the 21st century. Frost simulations showed that the length of the soil frost period would lessen all over the country. Though winters will be warmer, the associated decrease in snow cover in southern Finland will increase the probability of frozen ground there in the middle of winter compared with the current climate. In central and northern Finland there will be so much snow, even in the future, that the maximum annual soil frost depth will decrease there.

KEY WORDS: Climate change · Soil frost · Soil freezing · Snow cover · Hydraulic frost model · Scots pine

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1. INTRODUCTION

Within 100 yr the greenhouse-gas-induced global climate change is estimated to raise the temperature of the coldest winter months in Scandinavia by several degrees Celsius. This will be accompanied by a wintertime precipitation increase of 10% or more (e.g. Kettunen et al. 1988, Carter et al. 1996, Räisänen et al. 1999). The more rainy and milder weather will influence the depth and duration of soil frost. Changes in climate may also have an influence on the vegetation and soil properties that may have some minor influence on the occurrence of soil frost.

The climate scenarios based on transient general circulation models suggest major changes in the distribution of permafrost in the northern hemisphere. The poleward movement of the permafrost zones is clear,

and the systematic increase in the thickness of the seasonally thawed layer of the permafrost could release large amounts of CO₂ into the atmosphere (e.g. Woo et al. 1992, Anisimov & Nelson 1997). The potential change in the depth and duration of soil frost in the seasonal soil frost zone may also have large ecological and economical consequences. Soil frost affects, for example, the costs of the construction of buildings and roads: these costs are higher for frozen soil because the foundations for construction in the seasonal soil frost zone must extend to levels deeper than the maximum depth of soil frost. On the other hand, soil frost enables timber harvesting from locations where the soil would not bear heavy machines unless it were frozen. Heavy machines may also damage tree roots if the soil is unfrozen. Soil frost also enhances tree anchorage, i.e. during the period of frozen soil, trees have been found to suffer much less wind damage compared to in the unfrozen soil period (Laiho 1987).

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The modelling of frost in the soil profile under snow-free surfaces can be done with the help of the frost sum and soil properties (e.g. Saarelainen 1992, McCormick 1993, Venäläinen et al. 2001). The frost sum is the sum of below-0°C daily mean temperatures calculated from the beginning of the frost period. In Scandinavia the frost period typically starts in October and ends in May, in northern Lapland in June. If there is snow on the ground, the modelling of soil temperature becomes more complex. Models must include many variables describing both meteorological conditions, such as air temperature, short and long wave radiation, amount and type of snow, and soil characteristics, such as thermal conductivity and soil heat capacity (e.g. Bonan 1991, Cox et al. 1999). The influence of snow cover on temperature is illustrated in Fig. 1. The daily variation of air temperature in the case of late winter conditions can be more than 20°C, whereas at a depth of 80 cm below the snow surface the daily cycle is practically negligible.

Jansson (1991) introduced a comprehensive soil model known as SOIL that includes the processes relevant for the calculation of soil temperature. Kellomäki & Väisänen (1997) have integrated this SOIL model into a process-based forest ecosystem model (FinnFor), which links ecosystem dynamics with climate through selected physiological processes. Peltola et al. (1999) used this model when they studied the consequences of climate warming on soil frost and on the windthrow risk for trees in different geographical locations in Finland.

Peltola et al. (1999) used 2 options for climate warming: the increase of temperature was estimated to be either 2 or 4°C. In their computations, precipitation also increased slightly during the winter, due to an increase in cloudiness based on the assumptions behind the weather simulator that was used to provide climate scenario data (Strandman et al. 1993, see also Kellomäki & Väisänen 1997). According to Peltola et al. (1999), soil frost will decrease to an extent that will lead to a substantial increase in the windthrow risk for trees over the whole of Finland. Also Venäläinen et al. (2001) suggested that in the future soil frost would be shallower and the soil would be frozen for a shorter period annually under snow free surfaces; this may have an influence, for example, on the construction of roads in the future.

In contrast to Peltola et al. (1999) and Venäläinen et al. (2001), Isard & Schaetzl (1998), who examined the effects of winter weather conditions on soil freezing in southern Michigan in the USA, found that climate warming would, in spite of the temperature rise, actually increase soil freezing because the climate would become drier and thus the amount of snowfall would decrease. Their results were based on model simulations made with a hydrological/soil-temperature model (Isard & Schaetzl 1995).

This study aims to assess the potential impacts of climate warming on the depth and duration of soil frost under snow cover in forests growing at different geographical locations in Finland. Frost simulations are

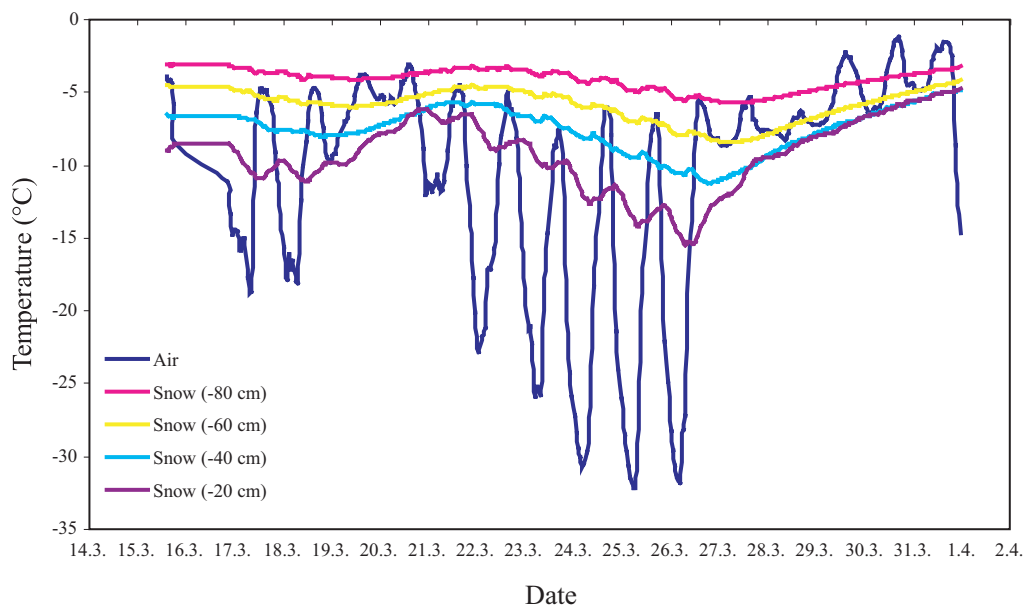


Fig. 1. Temperature at a height of 2 m above the snow surface (Air) and at depths of 20, 40, 60 and 80 cm below the snow surface as measured at Sodankylä (67° 22' N, 26° 37' E) between 15 March and 1 April 1997 (Heikinheimo et al. 1999)

made for Scots pine *Pinus sylvestris* L. stands using a process-based forest ecosystem model (FinnFor). Atmosphere-ocean general circulation models (AOGCMs) are the best methods available for estimating how the climate will change during the 21st century (Kattenberg et al. 1996). At high latitudes, such as 60 to 70° N, where Finland is situated, the grid size in these global climate models is generally about 300 km or more. In the current study, to obtain a spatially more detailed description, the Hadley Centre's AOGCM (HadCM2) results were dynamically downscaled with the regional climate model of the Rossby Centre, Sweden (Johns et al. 1997, Räisänen et al. 1999). This enables a better description of features and processes important for the regional climate.

2. METHODS

2.1. Outlines of methods. The impacts of climatic warming on soil frost depth and duration throughout the year was simulated using a process-based forest ecosystem model (FinnFor) (Kellomäki et al. 1993, Kellomäki & Väisänen 1997). In the ecosystem model, the dynamics of the ecosystem are directly linked to climate through photosynthesis, respiration and transpiration and indirectly through the hydrological and nitrogen cycles. A detailed description of the model is given below only with respect to the soil frost calculation, as a thorough discussion of the properties of the SOIL model utilised in the overall model has already been presented by Jansson (1991) and Kellomäki & Väisänen (1997).

The forcing by atmospheric variables needed in the FinnFor model simulations are given by a weather simulator developed by Strandman et al. (1993). The weather simulator outputs the data either with a time step of 1 h, or as a daily mean, depending on the variable. As input the simulator uses temperature, precipitation, humidity, wind speed, cloudiness and radiation data. In the study the input weather data needed in the computations was based on climate model (HadCM2) scenarios.

2.2. FinnFor model for frost calculations. 2.2.1. Model description: The soil description in the FinnFor model follows basically that of the SOIL model developed by Jansson (1991). In the SOIL model, the humus and mineral soil is divided into 12 horizontally homogeneous layers (no change in soil properties with time). Heat and water conditions are modelled with partial differential equations solved by Euler integration (Jansson 1991, Kellomäki & Väisänen 1997).

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial z} \left[k_w \left(\frac{\partial p}{\partial z} + 1 \right) \right] \quad (1)$$

Water and temperature conditions in the soil layer are calculated assuming a steady-state heat flow between the soil and the snow pack (Kellomäki & Väisänen 1997):

$$\frac{\partial(CT)}{\partial t} - L_t r_i \frac{\partial w_i}{\partial t} = \frac{\partial}{\partial z} \left(k_h \frac{\partial T}{\partial z} \right) - C_w \frac{\partial(Tq)}{\partial z} \quad (2)$$

where C is the heat capacity ($\text{J m}^{-3} \text{ }^\circ\text{C}^{-1}$) of the soil layer concerned, C_w is the heat capacity of the water ($\text{J m}^{-3} \text{ }^\circ\text{C}^{-1}$), p is water tension (mm water), k_h is thermal conductivity ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$), k_w is hydraulic conductivity (m s^{-1}), L_t is the latent heat of freezing (J kg^{-1}), q is the water flow (m s^{-1}), r_i is the density of ice (kg m^{-3}), t is time (s), w is the volumetric water content ($\text{m}^3 \text{ m}^{-3}$), w_i is the ice content ($\text{m}^3 \text{ m}^{-3}$), T is the temperature ($^\circ\text{C}$) of the inorganic soil layer, and z is the thickness (m) of the inorganic soil layer.

The lower boundary conditions for soil temperature, i.e. the heat flow from the lowest layer and percolation from the lowest layer, are calculated from an analytical solution of the heat flow equation, based on the sine variation of the annual mean air temperature (Kellomäki & Väisänen 1997). The unsaturated hydraulic conductivity is obtained from the empirical equation of Mualem (1976) and the thermal conductivity is calculated from an equation presented by Kersten (1949) and de Vries (1975). The behaviour of the snow layer is modelled in terms of the hydrological and thermal processes modifying the snow cover, assuming that the snow layer is homogeneous. The total water content of the snow layer is divided into liquid and frozen water. The melting and freezing of the water in the snow is determined by air temperature, solar radiation, precipitation and surface-soil heat flow as determined by Jansson (1991).

The total heat content of the frozen soil is partitioned into latent and sensible heat portions according to an empirical freezing-point depression function for soil (r) (Jansson 1991):

$$r = \left(1 - \frac{E}{E_t} \right)^{b\lambda} \quad (3)$$

where r is expressed in terms of the ratio of the actual latent heat content to the latent heat content at -5°C , defining the minimum unfrozen soil water content in the model; b is an empirical constant that depends on the soil type; λ is the pore size distribution index; E_t is the total heat content at -5°C ; and E is the actual total heat content given by the heat flow equation.

Correspondingly, the sensible heat content (H) is (Jansson 1991)

$$H = E(1 - f_{\text{lat}})(1 - r) \quad (4)$$

where f_{lat} is the latent heat of ice as a fraction of the total heat content of the soil at -5°C .

The soil water flow under frozen conditions is based on an analogy between freezing/thawing and drying/wetting. Water potential and hydraulic conductivity are calculated from the unfrozen water content, which in turn is obtained from the freezing-point depression function r (Jansson 1991).

Peltola et al. (1999) used the SOIL model described above in their study. They found that the simulated soil frost results for the current climate conditions were generally in quite good agreement with the regular measurements of soil freezing, thawing and maximum depth of soil frost made by the Finnish Hydrological Office (Huttunen & Soveri 1993). In addition, the length of the period with frozen soil under natural conditions was simulated realistically with the SOIL model.

2.2.2. Weather variables for FinnFor simulations:

The forcing by atmospheric variables needed in the FinnFor model simulations is provided by a weather generator developed by Strandman et al. (1993). The validity of the simulator has been thoroughly discussed by Strandman et al. (1993). They demonstrated a very close correlation between the observed and computed values for temperature, cloudiness, radiation, precipitation, air humidity and windiness, based on the monthly values of the different weather factors. Only a brief discussion is therefore given below on how the downscaled HADCM2 data with a 6 h time step must be modified so that it can be used as input for the FinnFor computations.

As inputs the FinnFor model uses as input hourly values of air temperature, solar radiation, water vapour pressure, wind velocity and atmospheric CO₂. Cloudiness and precipitation calculations are done on a daily basis. The downscaled 6 h HADCM2 data were first averaged to give daily values. To obtain the needed hourly values, the diurnal patterns of the selected variables were then generated using the weather simulator as described by Strandman et al. (1993) in detail.

In the FinnFor model calculations, it was assumed that precipitation is snowfall if the air temperature was below -3°C ; if the temperature was between -3 and $+3^{\circ}\text{C}$, then 50% of precipitation was assumed to be snow and 50% liquid. In temperatures above $+3^{\circ}\text{C}$ all the precipitation was assumed to be liquid.

2.3. Conditions for model simulations. 2.3.1. Geographical location:

For the current study, 4 locations, Helsinki, Joensuu, Vaasa and Muonio, representing the different climatological conditions in the southern, central eastern, central western and northern regions, respectively, were selected (Fig. 2). In the southern (Helsinki) and central-western (Vaasa) locations, the mean annual maximum snow depth is between 30 and 40 cm. The average frost sum is below 20 000 h°C and the soil frost depth is typically 40 to 60 cm. In the central-eastern location (Joensuu) the frost sum is on average 30 000 h°C, but due to an average snow cover that is thicker than in southern and central-western Finland, the soil frost penetrates into a shallower layer.

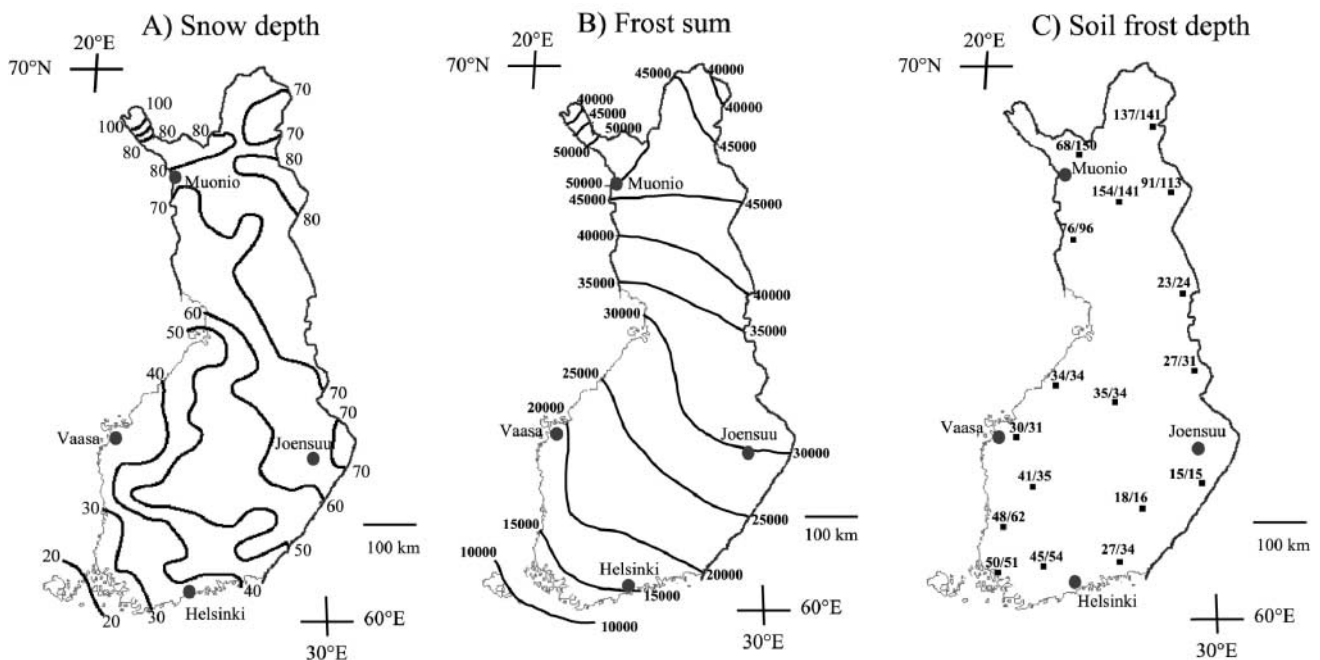


Fig. 2. Mean annual maximum snow depth (cm) during the period 1961–1990, mean annual frost sum (h°C) during the period 1971–1990 (Huttunen & Soveri 1993) and mean annual maximum soil frost depths in the open countryside/forest during the period 1971–1990 (Huttunen & Soveri 1993)

Typical maximum annual soil frost depths in central-eastern Finland are 15 to 20 cm. In northern Finland, both snow depth and frost sum have larger values than in central-eastern Finland, and on average the maximum annual soil frost depths are greater than 100 cm. The thickness of the snow cover is in general smaller in forests than in the open countryside. This should in principal mean that the soil frost penetrates deeper in forests than on fields. However, the local spatial variation of soil conditions seems to be so large that this effect cannot be seen in Fig. 2.

2.3.2. Climate scenarios: The Hadley Centre has produced several simulations with the HadCM2 AOGCM. The description of HadCM2 and its validation can be found in Johns et al. (1997). In this study two 240 yr HadCM2 simulations starting from 1860 were used. The first was a 'control run', in which the levels of greenhouse gases were held constant. Johns et al. (1997) state that the control run's climate should resemble present-day conditions. According to Räisänen (2000), HadCM2 performed well in a comparison in which control run climates of several AOGCMs were compared with observations in Northern Europe. The second was a 'GHG run', in which the increase of GHGs was as observed until 1990, followed by a constant annual increase of 1% (equivalent CO₂) thereafter. The effects of aerosols are not included.

In dynamical downscaling, a GCM run (in this case a HadCM2 run) is used to drive a regional climate model (in our case the Rossby Centre's regional model). The regional climate model has a finer resolution that enables a better description of features and processes important for the regional climate. Downscaling is a method for finding out what the coarse resolution results of global model look like on a finer scale. A more detailed description of dynamical downscaling can be found in, for example, Giorgi et al. (1994), Jones et al. (1997) and Rummukainen et al. (1998).

The regional climate model used at the Rossby Centre has been developed from the High Resolution Limited Area Model HIRLAM, version 2.5 (e.g. Källén 1996). The changes made to HIRLAM are summarized by Rummukainen et al. (1998). The results used in this study are from model version number 1 (RCA1) with a horizontal resolution of about 88 km (0.8° × 0.8° rotated latitude-longitude grid) covering Northern Europe. The same data were used by Venäläinen et al. (2001).

Dynamical downscaling has been done for a 10 yr time slice (2039–2049) from both the HadCM2 control and the GHG runs. The Rossby Centre's results for the 10 yr dynamically downscaled control run are referred to hereafter as CTRL, and the 10 yr time slice for the GHG run is hereafter called SCEN. The differences between SCEN and CTRL runs are expected to reveal the response of soil frost to the changed climate. How-

ever, the signal of the response is somewhat disguised by interdecadal variations in the climate. A longer integration period than 10 yr would reduce the noise (Räisänen & Döscher 1999).

Mitchell et al. (1999) have found out that the regional pattern of temperature change due to greenhouse gas forcing remains invariant (i.e. $\Delta T_{\text{regional}}/\Delta T_{\text{global}}$ is nearly constant) both over time and at different levels of greenhouse gas forcing in HadCM2. Assuming this, one can use the global annual mean temperature change in the timing of SCEN.

Hulme et al. (2000) have tuned a simple climate model to represent 7 AOGCMs. The simple model is forced by 6 SRES marker scenarios defined by the Intergovernmental Panel in Climate Change (IPCC 2000) to estimate global annual mean temperature changes from 1990 to 2100. The average temperature changes of the 7 AOGCM with the medium marker scenarios A1T, B2 and A1B are about 2.5, 2.7 and 2.9°C, respectively. In HadCM2 the global annual mean temperature corresponding to the SCEN time period increased by 2.6°C compared with CTRL, which is close to the increases in the simple model. Assuming A1T, B2, A1B or similarly sized emission scenarios and interpreting CTRL as the 'present climate' leads to the conclusion that SCEN roughly represents the climate at the end of the 21st century. If one assumes a faster (slower) emission scenario, the time of occurrence of SCEN moves some decades earlier (later).

The regional aspects of uncertainty in climate change were studied by analysing 8 AOGCMs simulations (IPCC-DDC 1999) forced with the IS92a greenhouse gas emission scenario (IPCC 1996). Four of the 8 simulations were performed with HadCM2 (a 4-member ensemble) and 1 of them was used in the downscaling. The range of wintertime temperature increase in Finland from the period 1961–1990 to the period 2070–2099 among the 8 AOGCM simulations was from 0.9 to 1.6 times the change in the HadCM2 ensemble mean. The range of precipitation change in the 8 simulations was from +16 to +40%. When compared with other AOGCMs, HadCM2 represents rather a moderate than a large change in the wintertime (November to March) climate in Finland.

The CTRL and SCEN data were further interpolated onto a higher resolution grid using a bilinear interpolation method. The cell size of this new grid was 0.333° in longitude and 0.166° in latitude. This grid size corresponds roughly to a square 15 km × 15 km grid. The values for the 4 locations (Fig. 2) that were used in the study were taken as the values of those grid squares inside which the studied stations were located.

2.3.3. Stand and soil data for frost simulations: The simulations were applied to a single 60 yr old Scots pine stand (height 17 m, diameter at breast height

16 cm, and stand density 1100 stems ha⁻¹) growing on a various Finnish moraine sand sites, i.e. in southern (Helsinki), central (east: Joensuu; west: Vaasa) and northern Finland (Muonio). The conditions in the forest represent a medium fertility site. In the simulations, 12 separate layers at 20 cm intervals beneath the soil surface are used. The soil was assumed to be frozen if the temperature was below 0°C.

3. RESULTS AND DISCUSSION

3.1. Soil frost in the current climate

The depth of soil frost is dependent on air temperature and snow depth, as well as on soil characteristics. The frost sum calculated assuming CTRL was found to be inside the natural multidecadal variability of temperatures and also represented the present-day climate in this respect. For another study (Venäläinen et al. 2001) frost sums based on the period 1974–1997 temperatures were calculated. When CTRL was compared with this data, it was found that in Helsinki the CTRL was colder than the period 1974–1997, whereas at Vaasa and Joensuu CTRL gave similar values to the observations and at Muonio CTRL was warmer than the period 1974–1997.

In Figs. 3 to 6 snow thickness and soil frost depths under CTRL and SCEN conditions are given. The iso-lines in the figures are probabilities based on the 10 yr data sets. The 50% percentile is considered to represent the average value for the period studied. In the current climate, in southern Finland (Helsinki) the average annual maximum snow depth in CTRL is about 30 cm (Fig. 3), while according to observations it is about 35 cm (Fig. 2). In central Finland (Joensuu and Vaasa) the CTRL snow depth is on average about 60 and 30 cm (Figs. 4 & 5), while according to observations it is about 65 and 35 cm (Fig. 2), respectively. In northern Finland (Muonio) CTRL predicts a mean maximum annual snow depth of about 65 to 70 cm (Fig. 6), while according to observations it is 70 to 80 cm (Fig. 2). The conclusion to be drawn is that the snow depths according to CTRL are slightly less than those observed during the period 1961–1990. However, the difference is so small that the CTRL run can be said to represent the observed climate well in this respect.

The mean maximum annual depth of soil frost according to CTRL in southern Finland (Helsinki) is below 20 cm, and in central Finland (Joensuu and Vaasa) also about 20 cm. The probability of very deep soil frost (more than 100 cm) is larger at Vaasa (about 20%) than at Joensuu (less than 5%) due to the shal-

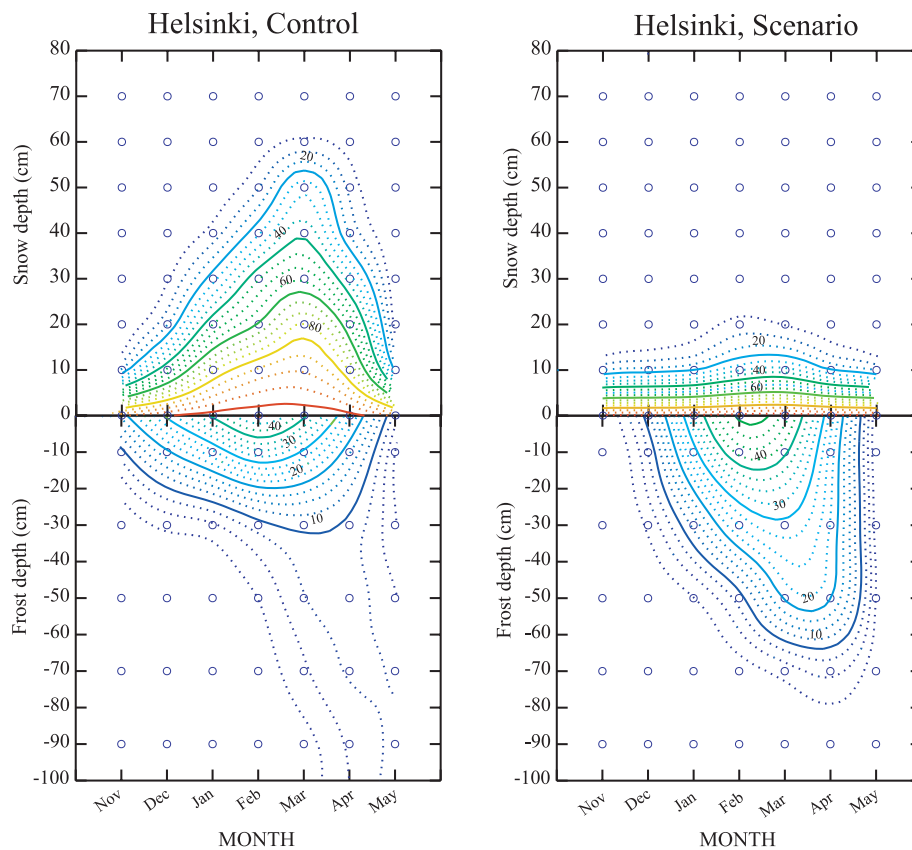


Fig. 3. Probability (%) of snow depth and soil frost depth in CTRL and SCEN climatological conditions in Helsinki

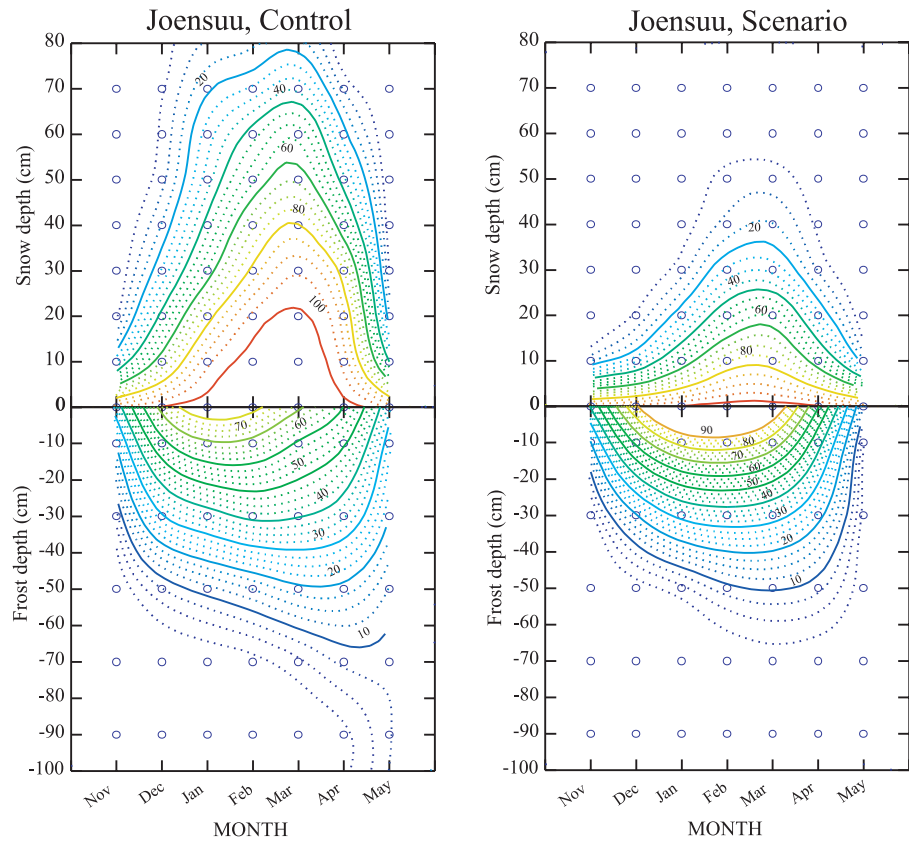


Fig. 4. Probability (%) of snow depth and soil frost depth in CTRL and SCEN climatological conditions at Joensuu

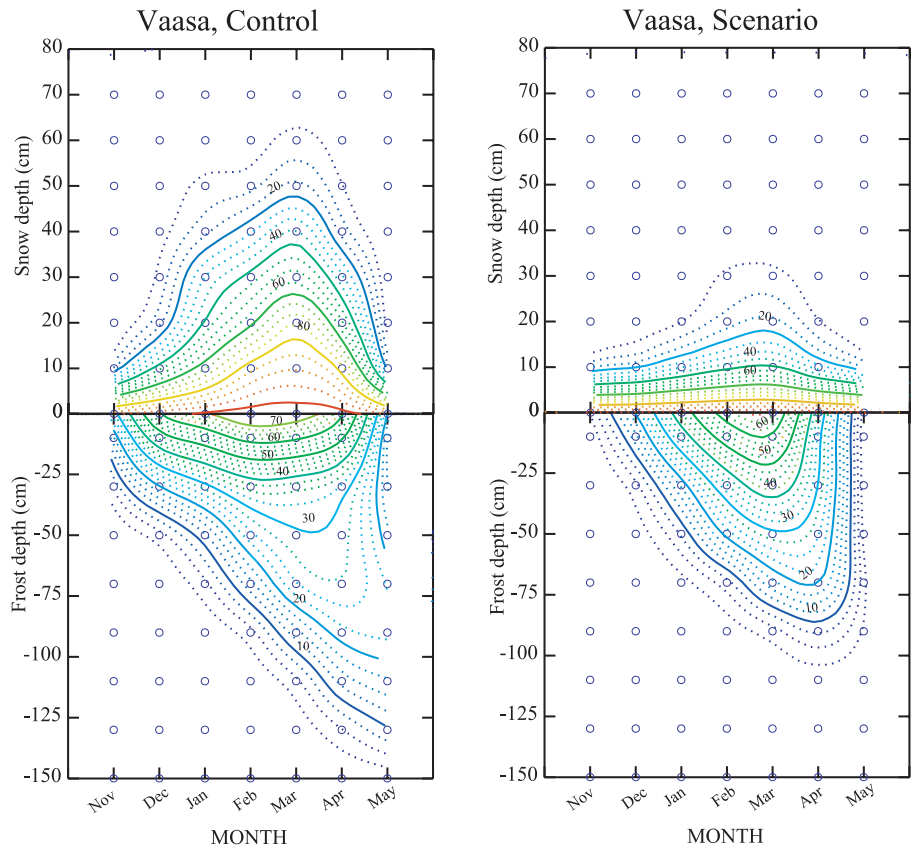


Fig. 5. Probability (%) of snow depth and soil frost depth in CTRL and SCEN climatological conditions at Vaasa

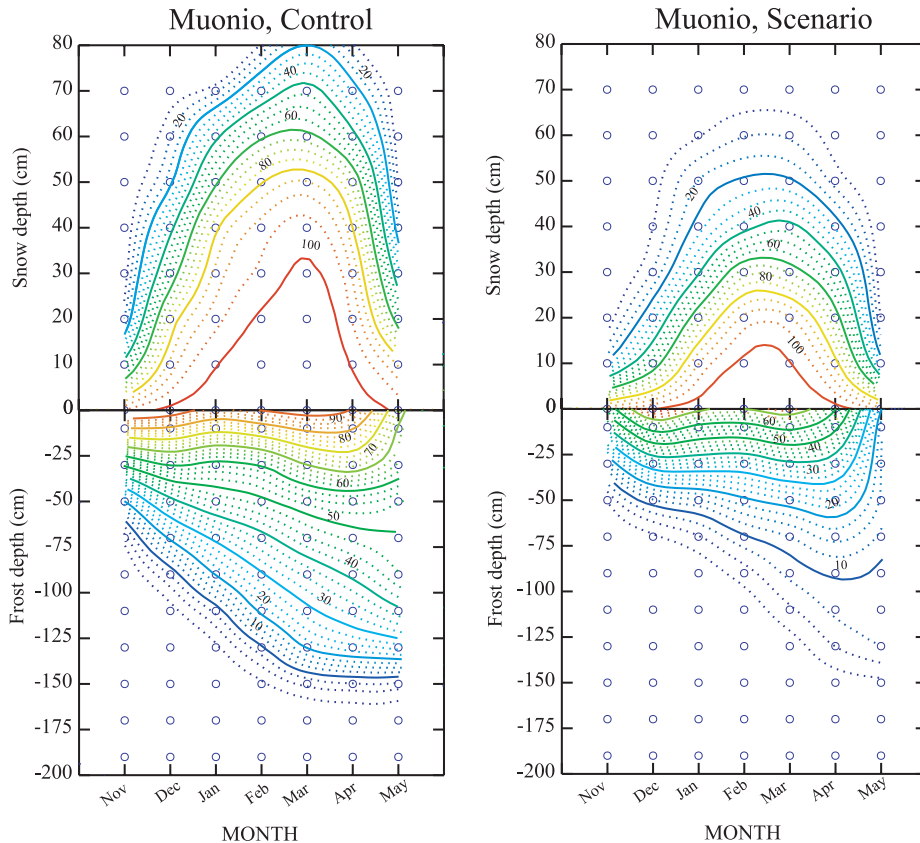


Fig. 6. Probability (%) of snow depth and soil frost depth in CTRL and SCEN climatological conditions at Muonio

lower snow cover in western Finland than in eastern Finland. In northern Finland the mean depth of soil frost according to CTRL is (Muonio) about 70 cm. In southern Finland (Helsinki) and in central-western Finland (Vaasa) the mean maximum soil frost according to CTRL is smaller than that observed, while in northern Finland (Muonio) and in central-eastern Finland (Joensuu) the observed values are near those of CTRL (Figs. 3 to 6).

In general, both the simulated weather conditions (HadCM2 model runs downscaled to the regional level) and soil frost estimates (the FinnFor model) under the simulated current climate are in fairly good agreement with the measurements made. The corresponding predictions for elevated temperature conditions were therefore judged to be acceptable for the present purposes.

3.2. Soil frost in the changed climatological conditions

According to the climate scenario used in this work, precipitation in the period November–April will increase by a few percent in southern Finland and by about 30% in northern Finland. At the same time, the average temperature is estimated to rise 4–5°C. The

spatial variation of temperature and precipitation change according to the scenario used in this work can be found, for example, in Räisänen et al. (1999).

Under the future climate conditions (SCEN), the snow depth is estimated to decrease at all locations due to warming. In southern Finland (Helsinki) the annual frozen period is estimated to shorten, but on the other hand the probability that frost penetrates deeper than in CTRL will increase, according to the simulations. In CTRL the probability of a soil frost depth of 60 cm is only a few percent, whereas in SCEN it is about 10% (Fig. 3).

In central-eastern Finland (Joensuu) the mean annual maximum snow depth according to SCEN will only be about 20 cm. The mean maximum annual frost depth is about the same in both CTRL and in SCEN. According to SCEN, the soil frost will never be deeper than 60 cm, whereas according to CTRL it can even be 100 cm. According to these results it is very obvious that the soil will be frozen every winter, but on the other hand deep soil frost depths will hardly ever occur. The length of the soil frost period will also shorten (Fig. 4).

In central-western Finland (Vaasa) the mean maximum annual snow depth in SCEN will be about 5 cm and the mean annual maximum soil frost depth about 25 cm. The soil frost period will shorten, as at the other

stations, and extreme soil frost depths will become improbable (Fig. 5).

According to SCEN, there will still be so much snow in northern Finland (Muonio) that the snow will be able to effectively protect the soil surface; as the climate becomes warmer, the soil frost there will be reduced. The mean annual soil frost depth will only be about 10 to 15 cm, whereas it is now 60 to 70 cm. Under this scenario the conditions in northern Finland will resemble those currently seen in eastern Finland (Fig. 6).

For Southern Finland, the results of Isard & Schaetzl (1998) are similar to the results of the current study: the reduced snow cover will increase soil frost. In the study of Peltola et al. (1999) the climate warming led to decreased soil frost. This is also the case in this study for central and northern Finland. In Peltola et al. (1999) the slight increase in precipitation in the wintertime also slightly increased the snow cover, leading to the difference between the results of the current study and theirs.

Relatively little attention has been paid previously to the impacts of climate warming on soil frost, and therefore there are few studies available for comparison. There are still large uncertainties related to the simulations of future climate on the regional scale, as explained in Section 2.3. The estimates on how the ground frost depth at the end of the 21st century will be different from the present day conditions cannot therefore be absolutely accurate. In any case, it seems evident that the global climate change will have an influence on soil frost conditions, and that the changes may have large ecological and economical consequences in the future.

4. CONCLUSIONS

The length of the soil frost period will shorten over all of the country if the predicted warming occurs. Though winters will be warmer, the associated decrease in snow cover in southern Finland would increase the probability of frozen ground in the middle of winter, compared with the current climate. In central and northern Finland, according to the climate scenario, there will be so much snow that the maximum annual soil frost depth will decrease. Under this scenario, the conditions in Lapland at the end of 21st century would resemble the conditions prevailing currently in eastern Finland. The results of the study demonstrate that when the influences of climate change are estimated, all relevant aspects must be taken into account. For example, if only air temperature were to be used for the estimation of soil frost, the results would be different compared with the case when changes in snow cover are also included in the study.

Acknowledgements. The regional climate model data for the study was provided by the Rossby Centre, located at the Swedish Meteorological and Hydrological Institute; we gratefully acknowledge the personnel of the centre. Special thanks are due to Dr J. Räisänen (Rossby Centre) and Ms A. Juottonen (Finnish Meteorological Institute) for their contribution in the processing of the climate model data.

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Editorial responsibility: Hans von Storch, Geesthacht, Germany

*Submitted: May 28, 2000; Accepted: November 28, 2000
Proofs received from author(s): February 26, 2001*