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Abstract

The aim was to use the COUP model to simulate soil heat and water processes under different snow and soil frost conditions. The calibration data for the study was collected in a snow manipulation study in a 47-year old stand of Norway spruce located in the eastern part of Finland. The COUP model simulations were able to illustrate the typical effects of freezing and thawing in terms of soil temperature, snow cover and water content. The model was capable to produce good predictions for the control plots without any interference of the snow cover as well for artifi cial plots with snow cover removed. However, simulated soil frost depth and water balance had some lacks in their predictions. One source of error relied in the meteorological input data, because the precipitation and relative humidity time series were not considered to be well representative of the study area. In addition, the model results were likely affected by the net radiation and cloudiness data, which were measured away from the study site. More measurement points in each plot and at different depths could aid in a more detailed calibration of the model. Despite these deficiencies the dataset as a whole met quite well the model input requirements. Essential parameters that the model needs to run can be readily determined and easily introduced in the model. The simulations can be further improved through some changes in the calibration process and/or through validating the model with additional independent data. In conclusion, the COUP model proved to be a functional tool for the simulation of heat and water soil processes. It is easy to manage, well organized and capable to simulate a range of soil situations by defining only few parameters and conditions.

Keywords

Climate change, COUP, modelling, Norway spruce, precipitation, snow cover, soil frost, soil moisture, soil temperature

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Contents

Abstract

The aim of the work was to use the coupled heat and mass transfer model, i.e. the COUP model, to simulate soil heat and water processes under different snow and soil frost conditions and to compare the simulation results with the measured data. The calibration data for the study was collected in a snow manipulation study in a 47-year-old stand of Norway spruce (*Picea abies* (L.) Karst.) located in eastern Finland. The COUP model simulations were able to illustrate the typical effects of freezing and thawing in terms of soil temperature, snow cover and water content. The model was capable of producing good predictions for the control plots without any interference of the snow cover, as well for artificial plots with the snow cover removed. However, simulated soil frost depth and water balance had some deficiencies in their predictions. One source of error originated from the meteorological input data, because the precipitation and relative humidity time series were not considered to be well representative of the study area. In addition, the model results were likely affected by the net radiation and cloudiness data, which did not originate from the study site. More measurement points in each plot and at different depths could aid in a more detailed calibration of the model. Despite these deficiencies the dataset, as a whole, achieved the model input requirements to a large degree. Essential parameters that the model requires in order to run can be readily determined and easily introduced. The simulations can be further improved through some changes in the calibration process and/or through validating the model with additional independent data. In conclusion, the COUP model proved to be a functional tool for the simulation of heat and water soil processes. It is easy to manage, well organized and capable of simulating a range of soil situations by defining only a few parameters and conditions.

Keywords: climate change, COUP, modelling, Norway spruce, precipitation, snow cover, soil frost, soil moisture, soil temperature

Introduction

Soil frost is common in wide areas on the Earth, with its depth and duration depending on year, location, vegetation, soil texture, soil moisture content, and snow depth. Approximately 55% of the land surface in the northern hemisphere is covered by seasonally frozen soil that may last from a few weeks to several months (Zhang et al. 2003). There are areas with shallow snow cover where the soil may freeze deeply (e.g. Soveri and Varjo 1977, Zhang 2005). In areas with deep snow cover soil may stay unfrozen throughout the winter. Permafrost is common: It occupies approximately 24% of the land surface in the northern hemisphere (Péwé 1979, Zhang et al. 2003). In such areas, just the upper layer of the soil may thaw during the warmest period enabling tree growth, however, according to the current IPCC report this situation may change as a result of the climate warming (IPCC 2007).

Considerable uncertainties hamper the predictions of the future soil frost and snow cover (Räisänen 2007). It is probable that the soil temperature and moisture will change in wide areas, followed by changes in carbon fluxes between the soil and atmosphere. According to the climate change projections, e.g. for Finland, winter temperatures will increase together with increased precipitation. Regional changes in snow cover are the immediate consequences of such a development. The regions with deep snow cover in the present climate may have a shallow or no snow cover with deep water-saturated soil frost in the future (Venäläinen et al. 2001a, b). However, because of the low incoming irradiation at northern latitudes, winters with extremely low temperatures are still probable in the future. Such a development would change the regional distribution of soil frost, i.e. deep soil frost starts to occur in the areas where the frozen layer is shallow in the present climate (Tierney et al. 2001). Reduced albedo, due to the lack of snow cover, promotes the absorption of solar irradiation and increases soil temperature that could favour early physiological activity of roots in spring. However, this positive effect may be lost due to hypoxic condition of the soil as a result of the increased precipitation and freeze-thaw events.

Under shallow snow cover with low soil temperatures, soil frost may damage the fine roots and reduce tree growth (Groffman et al. 2001, Tierney et al. 2001). Frozen soil effectively impedes water and nutrient uptake in the roots, and may cause stress on trees in spring when the air temperature temporarily rises quite high as a result of the strong daily photon flux density (Jarvis and Linder 2000, Repo et al. 2005, 2007, 2008). It has been proposed that the better growth of trees in some areas could be explained with deep snow cover and shallow soil frost, compared to areas with shallow snow cover and deep soil frost (Solantie 2003). The occurrence of deep snow cover is particularly found in eastern Finland with its continental climate, whereas shallow snow cover and deep soil frost are common in the western part of the country. Tree growth seemed not to follow the predictions made solely according to the effective air temperature sum, but the predictions were improved if the depth of soil frost was included in the model (Solantie 2003). In addition to the direct effects on tree roots, soil freezing also affects microbial mortality, mineralization of organic matter, retention or leaching of nutrients, and soil-atmosphere gas exchange (Groffman et al. 2001, Tierney et al. 2001).

Predicting the soil frost conditions for the future may be made using mathematical modelling. The outputs of such a model may be used for predicting tree growth in changing soil temperature conditions. The aim of this study was to use the COUP model (Jansson and Karlberg 2001) to simulate soil heat and water processes under different snow and frost conditions in a stand of Norway spruce in eastern Finland. The objective was to formulate a simulation model for describing the variation of soil temperature and water content at different soil depths with different snow cover conditions using a dataset of meteorological variables measured over two years, soil temperature, soil moisture, and snow depth. The intention was to apply the COUP model to simulate soil processes and determine soil and vegetation input conditions that agree with the reality as closely as possible. At the same time, the model was used to assess the quality of the measured data. The model was validated by comparing the simulation results with the measured data, i.e. soil temperature, soil moisture content, snow depth and snow water equivalent. The hypothesis was that the simulations with the COUP model can illustrate the typical effects of seasonal soil freezing and thawing on heat and water processes in a Norway spruce forest under two treatments: 1) under undisturbed snow situation (CTRL) and 2) under a situation where snow was removed in winter (OPEN).

Material and methods

1. Description of the site

The data for the study was collected in an experimental area in Jaamankangas (62º36'N, 29º43'E, 84 m above sea level (a.s.l.)) located in eastern Finland. The experiment was established in 2005 in a flat (slope=0) 47 year old stand of Norway spruce with the following stand characteristics: canopy height of 17-20 m, stand volume of 211 m^3/ha, stand density of 864 trees/ha, basal area of 25.4 m^2/ha, and root depths of 20-30 cm. The soil profile was subdivided into three layers (along with the depth): organic, organic-mineral, and mineral layers with thicknesses of 4, 19 and 35 cm, respectively. The texture of the second and third layers was defined (Table 1). The porosity was considered to be 50%. In the model a mean texture was introduced for each layer.

Table 1. Soil texture in two upper mineral layers.

	Organic-mineral, %	Mineral, %
Clay	2	3
Silt	23	25
Sand	66	48
Coarse sand	9	24

The experiment included nine sample plots of three different snow treatments with three replicates for each treatment (Maljanen et al. 2010). The treatments were the following: undisturbed snow accumulation and melt (CTRL), removed snow cover by shovelling during the winter (OPEN), and removed snow during the winter and ground insulation at the end of March (FROST). In this study only CTRL and OPEN treatments were considered because the insulation of FROST treatment could not be simulated by the COUP model due to unavailability of the thermal properties of the insulator. Thus, in the 6 sample plots daily soil temperature at depths of 5, 15 and 50 cm by Pt-100 thermistors (Campbell Scientific) and volumetric water content (% volume) at a depth of 15 cm by TDRs (CS616, Campbell Scientific) were recorded and compared with the computed values for the period from October 27, 2005 to June 13, 2008. A measuring rod was set in the middle of each CTRL plot and 16 discrete daily measurements of the snow depth were taken during the winter of 2005-2006 and 2006-2007. In addition, snow water equivalent (mm) was assessed in the middle of the CTRL plots five times during the winter of 2006-2007.

2. Meteorological data

The weather data included air temperature (ºC), precipitation (mm/h), relative humidity (%), global radiation (J s^{-1} m^{-2}) and wind speed (m s^{-1}) from January 1, 2005 to December 31, 2007. The air temperature at the experimental site was recorded at a height of 2 m. The wind speed was recorded at Joensuu Airport (10 km south of the experimental site) at a height of 10 m above the ground for the years 2006 and 2007. The wind speed during 2005 was calculated as an average of 2006 and 2007 data and was set as a constant value throughout the year. The rest of the meteorological data was obtained from the meteorological station in Niittylahti near lake Pyhäselkä (20 km south of the experimental site, ca. 80 m a.s.l.).

3. COUP model description

The COUP model is the latest version of SOIL, WINSOIL, and SOILN models. Its aims are the calculation of vertical heat and water fluxes in soil-snow-vegetation-atmosphere system. It is based on the numerical solution of the differential equations for water and heat flow. The model is capable of simulating these processes in different soils (bare or covered by vegetation) using a one-dimensional soil column parameterisation. The explanation of the model for each specific process, as well as its inputs (parameters and switches) and outputs are explained in the web page: http://www.lwr.kth.se/vara%20datorprogram/CoupModel/index.htm. It is possible to download the program from the web page, additionally it provides the same documentation as contained in the program help files. The downloaded program comes with tutorials for specific cases, which are helpful to understand how the program works and which inputs can be chosen in each case. This material is useful for beginners to start to work with an environmental simulation model. The modelling process was developed following three main steps: i) familiarization with the functionality and procedures of the COUP model (using the documentation explained above) ii) setup of the first driving files and parameterization of the model (first considering a bare soil and then including vegetation) and iii) development of a model calibration in order to improve its outputs. Points ii) and iii) are explained in the following two sections.

4. Model settings and operability

The model menu system is displayed in different tab sheets which contain input and output information. The tab sheets used in the present study are the following: run info, switches, parameters, parameter tables, model files, output variables, and validation. The first step, when a new worksheet opens, is to go to the Menu bar/Configurations/User Setup. To set up the simulations for the present study the User Level "Experienced" was chosen. The functionality of each section is explained below in the order of use.

1) Run info

The run info sheet refers to general information for the simulation. The blue-coloured fields always show information that can be changed or has been changed and saved. The start date and end date of the simulation are linked to the driving file and measured data. The driving file contains input meteorological variables that are forcing the simulation. According to available meteorological data the simulations were conducted for the period from October 27, 2005 to December 31, 2007. The measured input data are the daily mean values, and thus the Input Time Resolution is "Daily mean values". Here "Days" are labelled as "1" and Minutes as "0". The Number of Iterations is labelled as "32" per day. The button to start the simulation is on the top-left of this section coloured as yellow ("Make Single Run").

2) Model files

In this sheet the driving files for the simulations will be introduced. The files must be in a binary format (.BIN). In order to make the conversion into the binary format, firstly the data have to be prepared in the following way: As a first step, the data have to be in an ASCII-formatted .DAT file. The date numbers have to be written as '*yyyymmdd*' and the name tags of each data series (e.g. temperature, precipitation, etc.) have to be removed from the .DAT file. Afterwards, the .DAT file will be opened with the PG program (clicking the right button of the mouse). The PG is a binary program which is used to introduce the input data into the COUP model. The answers to the questions in the PG program after its execution are the following:

- Answer (1-6): 2 (enter)
- Enter number of variables: number of data file variables without considering the date. (enter)
- Is century specified in input data? Y (enter)
- Specify format: r (enter)

Then, there a message appears such as “If your variable description is stored in a sequential file Enter file name:” (enter). At this point, the user can introduce the name, units, and identification of the data. It is important to introduce these values for the driving files ONLY, as is defined in the documentation (see http://www.lwr.kth.se/vara%20datorprogram/CoupModel/NetHelp/default.htm, Common Characteristics/ Meteorological data/Files/Meteorological_Data or Snow depths (in our particular case)).

In the present study the driving files introduced were the meteorological and snow depth data, which depended on the type of plot being simulated (CTRL or OPEN). Hence, for the CTRL plots the meteorological data were used as explained in Section 2. In the case of the OPEN plots the aim was to simulate the effects of snow removal while maintaining the same weather characteristics as in the CTRL plots. In order to describe snow removal, precipitation was first changed and set to a value of 0 mm/d (no snowfall) when the daily air temperature was below 0 °C. In addition, a driving file containing the snow depth was prepared to force the snow depth to be zero for each day of the simulation period. The driving files are introduced into the model by clicking on the “Meteorological data” bar and “Select PG file” bar. Then automatically the minimum and maximum values of the data file will appear in the sheet.

It is important to note that the measured output data also has to be changed into the binary format using the PG program, although it is not introduced in this Model files sheet but in the Validation sheet.

3) Switches

In this section the functions of each module of the model are selected according to the model’s documentation and the assumptions made in each particular simulation. The switches are related to parameters, parameter tables, or model files, so that the selection of one option can enable other options relevant for the simulation. Hence, the switches sheet is the first step in the simulation setup. The switches selected for the simulation of the CTRL and OPEN plots are explained in Tables 2 and 3, respectively.

The model was simplified at the first step in order to establish the heat and water patterns in a bare soil and subsequently vegetation was incorporated. The procedure was, firstly, to calibrate the model at CTRL plots and secondly, to apply similar conditions at OPEN plots and calibrate the model there.

During the modelling period, the switches were systematically changed to observe their effect on the snow depth and soil temperature results. Thus, vapour fluxes (Model Structure/SoilVapour/Soil-and SnowVapourflow) were incorporated to change the heat capacity as a function of the depth (Soil Thermal/ SolidHeatCapDist/f(z)), to consider a constant heat flow in the lower boundary (Soil heat flows/Lower Boundary/Constant heat flow), and to modify the snow properties (SnowPack/NewSnowDensity/ Exponential f(air temp) or SnowPack/SnowMeltFunction/Heat balance). However, these switches did not improve the model results and therefore they were excluded.

In sites without vegetation an Iterative Energy Balance method was defined to estimate soil evaporation (Soil evaporation/Evaporation Method/Iterative Energy Balance). Nevertheless, when vegetation was incorporated the Evaporation Method was not estimated since the Iterative Energy Balance switch produced inferior results.

In the case of the OPEN plots, the simulation of the snow removal was problematic. In order to characterise snow removal, attempts were made to switch off the snow pack, or the modelled snow depth was forced to match a hypothetical data with a constant daily snow depth of 0 mm. However the final solution was to force the snowfall values in precipitation data to zero as explained in the section above.

Table 2. Final switches determined for the CTRL plots. Other switches have been taken as default values for the model.

Group	Switch name	Value	Explanation
Drainage and deep percolation	LBoundUnSaturated	Unit Grad Flow	The saturated layer is located quite deep and the water flow is supposed to be gravitational
Interception	PrecInterception	On	It has to be considered to simulate the snow depth
	SnowInterception	On	
Meteorological Data	CloudInput	Estimated	
	CommonRefHeight	No	The wind and air temperature were taken from different reference heights
	HumRelInput	Read from PG-file (first position)	
	PrecInput	Read from PG-file (first position)	
	TempAirCycle	Annual	Because daily mean values are described in our data
	TempAirInput	Read from PG-file (first position)	
	VapourAirInput	As relative humidity	
Model Structure	Evaporation	Radiation input style	It is better to consider the radiation in snow situations
	PlantType	Explicit single big leaf	It is wanted to distinguish soil evaporation and transpiration and only there is one canopy
	Snow pack	On	
	WaterEq	On	
Plant	RootDistribution	Table	See Parameter table
Potential Transpiration	Aerodynamic Resistance	f(Monin-Obukhov length)	It is necessary to calculate a stability correction
	Displacement	f(canopy)	
	Roughness	f(canopy)	
Radiation properties	LongWaveBalance	Two separate formulas	Because global radiation input was specified as a driving file
Snow pack	SnowSurfTemperature	f(E-balance Solution)	It is recommended to simulate temperature and water conditions
Soil frost	FlowDomains	LowDomain	Due to sandy texture
Soil heat flows	Initial Heat Conditions	Temp(z)-Table	Took at 5, 15 and 50 m depth
Soil water flows	Initial water conditions	Uniform Water Content	Took only at 15 m depth

Table 3. Final switches determined for the OPEN plots. Other switches have been taken as default values for the model.

Group	Switch name	Value	Explanation
Drainage and deep percolation	LBoundUnSaturated	Unit Grad Flow	The saturated layer is deep and the water flow is supposed to be gravitational
Interception	PrecInterception	On	It has to be considered to simulate the snow depth
	SnowInterception	On	
Meteorological Data	CloudInput	Estimated	
	CommonRefHeight	No	The wind and air temperature were taken from different reference heights
	HumRelInput	Read from PG-file (first position)	
	PrecInput	Read from PG-file (first position)	
	TempAirCycle	Annual	Because daily mean values are described in our data
	TempAirInput	Read from PG-file (first position)	
	VapourAirInput	As relative humidity	
Model Structure	Evaporation	Radiation input style	It is better to consider the radiation in situations with lying snow
	PlantType	Explicit single big leaf	It is wanted to distinguish soil evaporation and transpiration, and there is one canopy only
	Snow pack	On	
	WaterEq	On	
Plant	RootDistribution	Table	See parameter table
Potential Transpiration	Aerodynamic Resistance	f(Monin-Obukhov length)	It is necessary to calculate a stability correction
	Displacement	f(canopy)	
	Roughness	f(canopy)	
Radiation properties	LongWaveBalance	Two separate formulas	Because global radiation input was specified as a driving file
Snow pack	SnowAdjustment	Forced to match continuous	Force the model to match to driving file snow_removed.bin
	SnowSurfTemperature	f(E-balance Solution)	It is recommended to simulate temperature and water conditions
Soil frost	FlowDomains	LowDomain	Due to sandy texture
Soil heat flows	Initial Heat Conditions	Temp(z)-Table	Taken at 5, 15 and 50 m depth
Soil water flows	Initial water conditions	Uniform Water Content	Taken only at 15 m depth

4) Parameters

Most parameter values represent coefficients in different functions, making it difficult to justifiably change their values. Some parameter values can be directly related to measurements. In the present study the model parameterization is described in Table 4. As seen in Table 4 the reference height of 2 m related to the air temperature and wind speed measurements is added to the canopy height to assume that the available meteorological data represents conditions above the canopy. One important parameter in this study was the thickness of the organic layer, which was doubled from the measured value to account for the effect of vegetation litter on the thermal properties of the top organic layer. Finally, the thermal conductivity of the organic layer (defined by parameters OrganicC1 and OrganicC2) was also assessed by comparing it against their literature values and obtaining a good agreement afterwards.

Table 4. Final parameters determined for the CTRL and OPEN plots. Other parameters have been taken as default values for the model. [a)] Not necessary to change, it is possible to leave the default values.

Group	Parameter name	Value CTRL	Value OPEN	Explanation
Meteorological Data	AltMetStation	120 m	120 m	
	AltSimPosition	120 m	120 m	
	ReferenceHeightTemp	20 m	20 m	2 m + canopy height (18 m)
	ReferenceHeightWind	28 m	28 m	10 m + canopy height (18 m)
	TempAirAmpl	20.82ºC	20.82ºC	Difference between mean and highest air temperature value [a)]
	TempAirMean	3.12 ºC	3.12 ºC	Mean air temperature of simulated period [a)]
	TempAirPhase	Day 22	Day 22	Coldest day of the year (day number) [a)]
Plant	AlbedoLeaf	20 %	20 %	Approx value for Norway spruce
Radiation properties	Latitude	62.31	62.31	
Soil Thermal	OrganicLayerThick	0.08 m	0.08 m	Organic layer thickness x 2
Soil heat flows	TempDiffPrec_Air	0 ºC	0 ºC	
Soil water flows	InitialWaterContent	12.5 vol-%	16.33 vol- %	

5) Parameter tables

The parameter tables are used to define the soil profile and plant canopy. In the present study the soil profile was subdivided into 10 computation layers in a soil column down to a depth of 1.06 m. The thicknesses of the first six layers from top to bottom were 0.03, 0.04, 0.05, 0.06, 0.10, and 0.14 m, while the thickness of the last four layers was 0.16 m. In some cases the simulation results can be improved, e.g. the simulation of the soil frost depth, with more layers and deeper soil column depths being used. The layer thicknesses are chosen in such a way that the middle points of some layers coincide with the depths of 5, 15 and 50 cm, where measurements of soil temperature are conducted. Thus, layer 2 (3-7 cm depth) has 5 cm as the middle point, layer 4 (12-18 cm depth) has 15 cm and layer 7 (42-58 cm depth) has 50 cm. The texture of the soil was defined in *Brooks-Corey, water retention, measured horizons* parameter table from the soil database that was recently created and called *16:1 Jaamankangas*. In the new soil data the thicknesses of the organic-mineral and mineral layers, as well as the mean texture and porosity of the layers were described. The canopy height was set to a mean value of 18 m and root depth to a value of 25 cm. The root fraction was calculated as a proportion between the thickness of each layer and the rood depth. Finally the canopy leaf area index (LAI) was calculated from the biomass estimate that is produced by a function for Norway spruce (Repola et al. 2007). The day number is normally adjusted to describe species-dependent growing season length. In the agricultural sites the growing season is short and describes crop growth over a summer season. In the present study, the growing season is multiple years since the forest species have a slower growth.

Table 5. Final parameters tables determined for the CTRL and OPEN plots. Tables and parameters not defined have been taken as default values for the model. The numbers in parenthesis represents the number of elements of each parameter table.

Group	Table Name	Parameters	Range of values	Explanation
Plant	Above ground characteristics with time (5)	DayNumber	1/90/185/270/365	Five particular days in a selected year
		LeafAreaIndex	5.5	Constant for whole year.
	Root depths development with time (5)	DayNumber	1/90/185/270/365	
		RootDepth	-0.25 m	Constant for whole year
	Root distribution with depth (10)	Root fraction	0.12 – 0.18 (fraction of one)	Only calculated for the 5 first layers since there are no roots in deeper layers.
Potential transpiration	Evapotranspiration – single canopy (5)	DayNumber	1/90/185/270/365	
		CanopyHeight	18 m	Constant for whole year.
Soil Hydraulic	Brooks-Corey, water retention, measured horizons (2)	Upper Depth	0/0.23 m	Organic-mineral layer (include organic layer)
		Lower depth	0.23/0.58 m	Mineral layer
		Other parameters change automatically		
	Brooks-Corey, water retention, model layers (10)	Change automatically		
	Hydraulic conductivity, measured horizons (2)	Change automatically		
	Hydraulic conductivity, model boundaries (10)	Change automatically		
Soil Profile	Compartment sizes (10)	Thickness Layers	0.03-0.16 m	
Soil heat flows	Initial temperatures (10)	Temperature	CTRL 0.55-4.92 ºC	Three values (5, 15 and 50 cm depth) distributed in 10 compartments. 1st day measure of plot CTRL2 or OPEN2
			OPEN 2.36-5.33 ºC	

5) Output Variables

This section lists the output variables that are printed by the model (Table 6). Some output variables were compared with the measured data, such as snow depth. Additionally some output variables were used to help assess the simulated water and heat processes.

Table 6. Outputs determined for the CTRL and OPEN plots. Numbers in parenthesis mean soil layers.

Type	Group	Output name	Units
Auxiliary variables	SnowPack	SnowWaterOutflow	mm day^{-1}
		TempSnowSurface	ºC
	Interception	InterceptionCapacity	mm
		InterceptionPotEva	mm day^{-1}
		InterceptionRate	mm day^{-1}
		Throughfall	mm day^{-1}
	Additional Variables	Evapotranspiration	mm day^{-1}
	Soil heat flows	Temperature (2),(4),(7)	ºC
	Soil frost	FrostLowerBoundary1	m
		FrostUpperBoundary1	m
	Soil water flows	TotalWaterContent (2),(4),(7)	vol %
		WaterContent (2),(4),(7)	vol %
Driving Variables	Meteorological Data	PrecCorrected	mm day^{-1}
		TemperatureAir	ºC
Flow Variables	Surface water	SoilInfil	mm day^{-1}
	Drainage and deep percolation	DeepPerc	mm day^{-1}
		TotalRunoff	mm day^{-1}
	Water uptake	Transpiration	mm day^{-1}
		WUptakeRate (2),(4),(7)	mm day^{-1}
	Soil water flows	SurfaceOutFlow	mm day^{-1}
		Waterflow (2),(4),(7)	mm day^{-1}
State Variables	SnowPack	SnowDepth	m
		TotalSnowMass	mm
	Additional Variables	WaterBalanceCheck	mm
	Surface water	SurfacePool	mm
	Soil water flows	WaterStorage (2),(4),(7)	mm

5) Validation

The COUP model allows the user to compare the simulations against the measured data. This property of the model was not used often in the present study since the model calibration was based on a manual comparison between the model results and the data in excel files. However the R^2 values, for example, were used as a reference in the calibration procedure. The PG files used in the validation were the measured data binary files selected from Validation sheet (Specify new validation file). Those files include all the repetitions of the experiment in order to see the variability of the measurements. Clicking the top yellow bar allows the user to link the measured data of each plot with the corresponding simulated data future outputs. In this case the temperature (at 5, 15 and 50 cm of depth), the water content (at 15 cm), the snow depth and the snow water equivalent were the tested variables.

Results

1. Soil temperature

The simulated soil temperature at different soil depths (5, 15 and 50 cm) under snow (CTRL) and without snow (OPEN) is presented in Figure 1. The COUP model reproduced the measured variation of soil temperature well in each layer. According to the simulations, during the summer the soil temperature at the depth of 5 cm was slightly lower than air temperature, which was the same for both treatments. On the other hand, the soil temperature during the winter was controlled by the snow depth, which acted as an insulator and resulted in temperature values near 0 ºC at the depth of 5 cm in the snow-covered plots. The soil temperature was much colder and closer to air temperature (around -15 ºC) in plots where the snow was removed. In general, the COUP model simulations were highly comparable with the measured data since the mean absolute error and bias were low and the mean measured range, which characterised the variability of the measurements at the same location and time, was similar to the mean absolute error (Figures 2, 3, 4 and Table 7). The bias values showed that the simulations tended to overestimate the soil temperatures in most cases. Under undisturbed snow accumulation, the overestimation of soil temperature was higher in winter 2006-2007 than in 2005-2006 due to the overestimation of simulated snow depth during 2006-2007 (see Figure 5). On the other hand, in cases when snow was removed, the underestimation in winter was compensated by the overestimation in summer which produced a seemingly low bias (0.02-0.06 ºC) over the entire simulation period.

The best temperature results for both treatments were developed in the simulations at the depth of 15 cm (Figure 3). The COUP model gave the worst predictions at the depth of 50 cm with a temperature mismatch increasing during the winter.

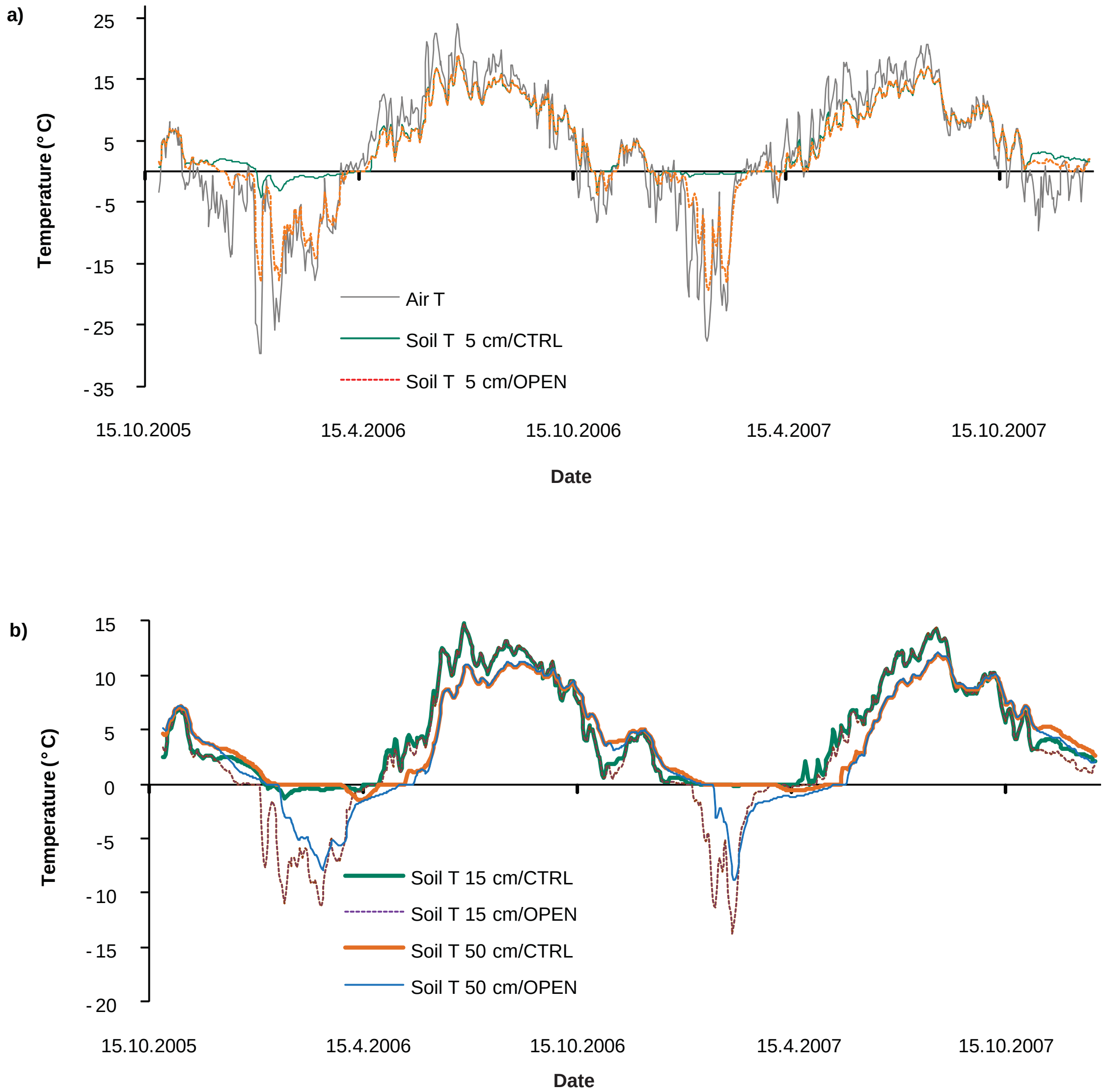
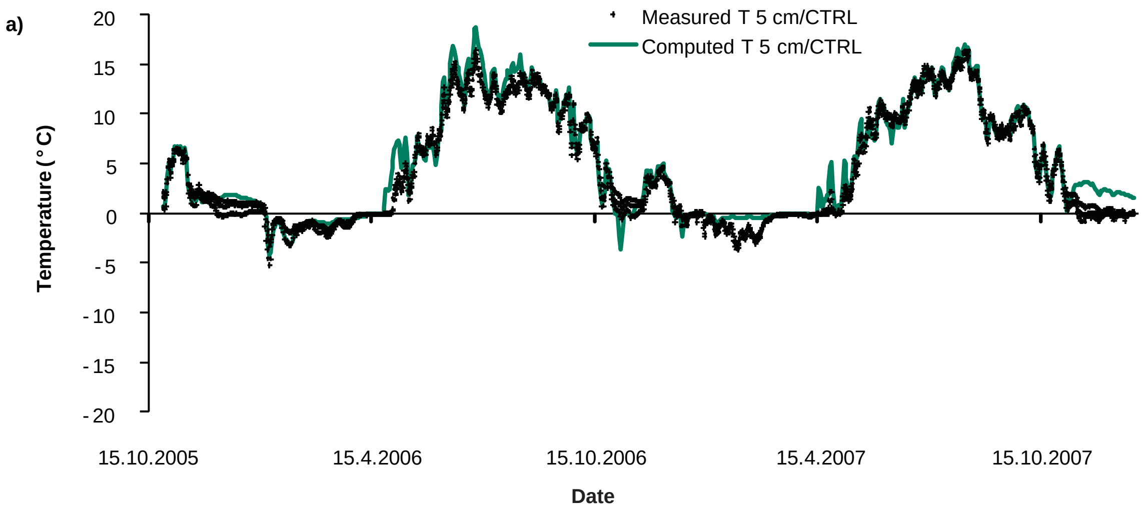


Figure 1. Measured air temperature and simulated soil temperature under undisturbed snow accumulation and removed snow situations (CTRL and OPEN plots respectively). a) Soil temperature at the depth of 5 cm and air temperature, and b) soil temperatures at the depths of 15 and 50 cm. T refers to temperature.

Table 7. Mean absolute error, bias and mean measured range of simulated soil temperatures at the depths of 5, 15 and 50 cm and for situations with (CTRL) and without (OPEN) snow cover.

Depth	**Treatment**	**Mean absolute error** (°C)	**Bias** (°C)	**Mean measured range** (°C)
5 cm depth	CTRL	0.80	0.56	0.60
	OPEN	1.20	0.02	0.66
15 cm depth	CTRL	0.73	0.29	0.57
	OPEN	0.78	0.06	0.43
50 cm depth	CTRL	0.92	-0.12	0.33
	OPEN	1.01	0.03	0.60



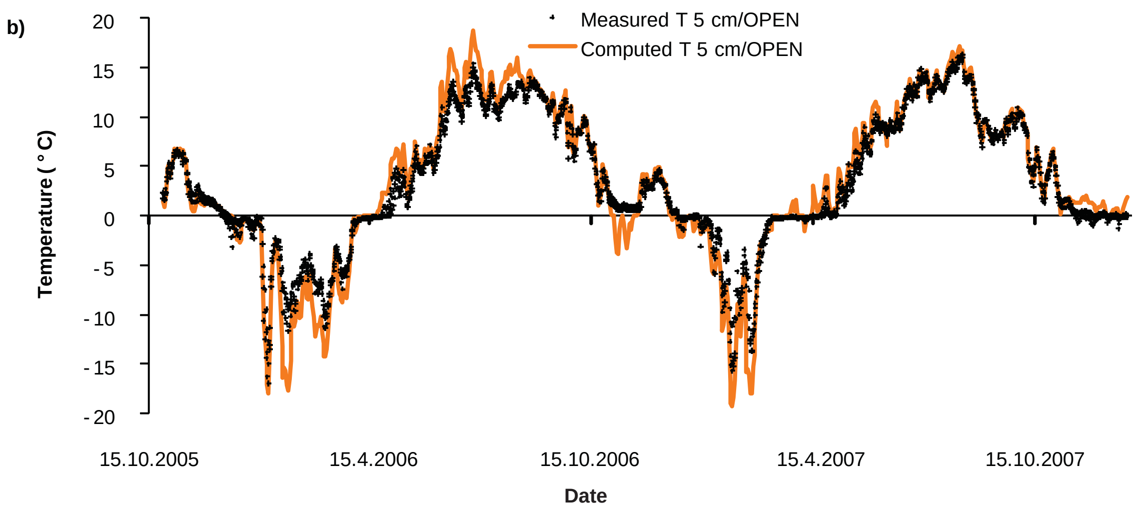


Figure 2. Simulated soil temperature as a solid line and measured values as points at the depth of 5 cm. a) Undisturbed snow accumulation (CTRL plots), and b) snow removed (OPEN plots). T refers to temperature.

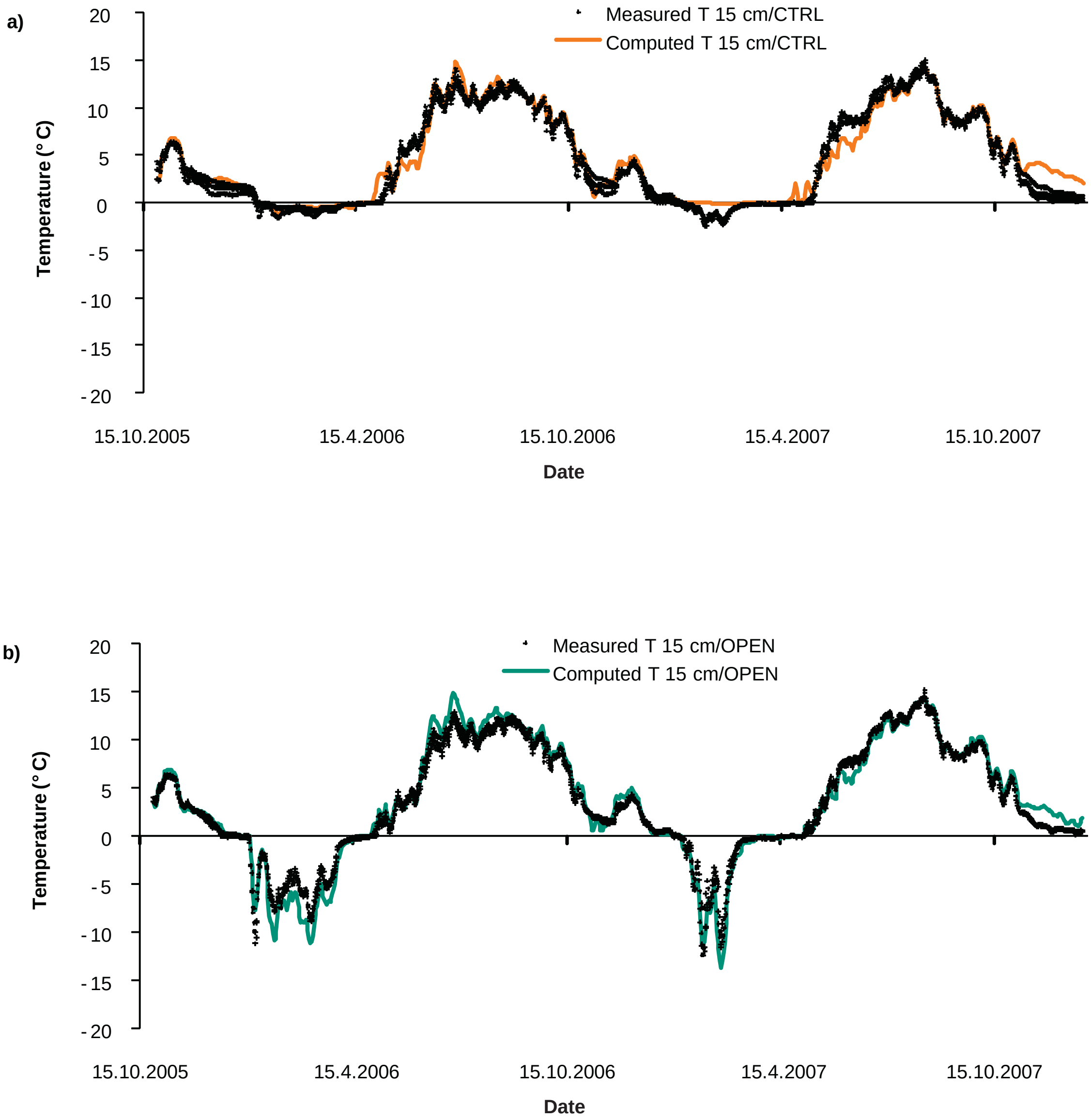
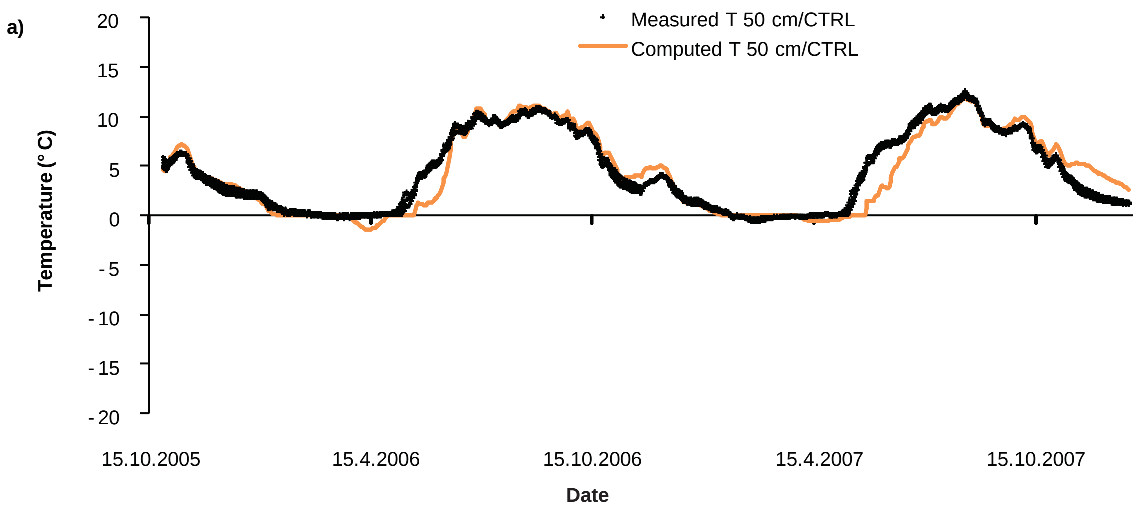


Figure 3. Simulated soil temperature as a solid line and measured values as points at the depth of 15 cm. a) Undisturbed snow accumulation (CTRL plots), and b) snow removed (OPEN plots). T refers to temperature.



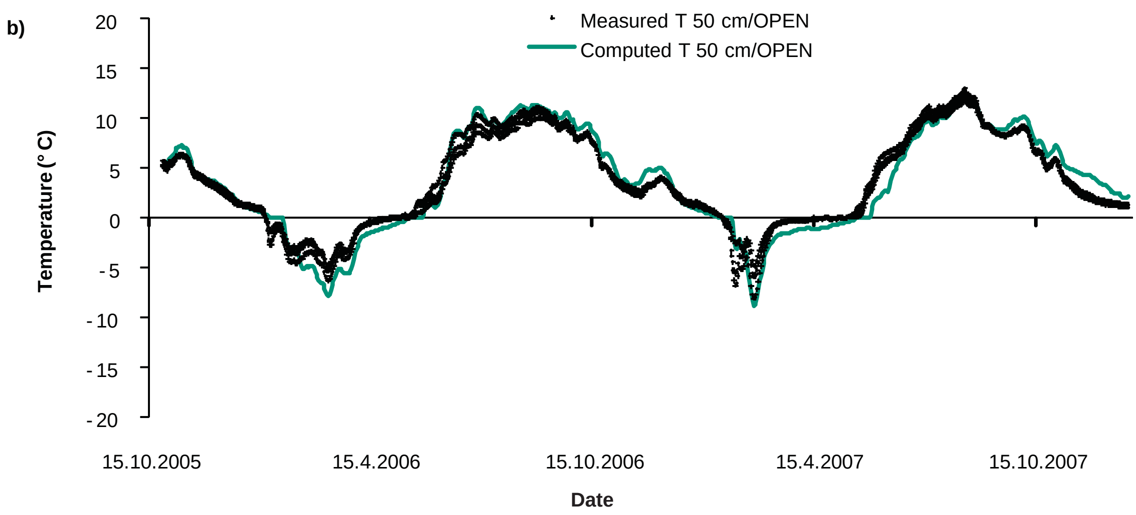


Figure 4. Simulated soil temperature as a solid line and measured values as points at the depth of 50 cm. a) Undisturbed snow accumulation (CTRL plots), and b) snow removed (OPEN plots). T refers to temperature.

2. Snow cover and frost depth

The COUP model did not exactly match the measured range of snow depth in the CTRL plots (Table 8, Figure 5). However, the mean absolute error was not high compared with the mean measured range, which demonstrated a fairly large variation between the measured values. The bias of the simulated snow depth was high, showing a large overestimation during the winter of 2006-2007. The overestimation was likely due to uncertainties in the precipitation data that was not available from the site. For the OPEN plots the model provided quite realistic representation for the snow depth although a complete removal of snow was not easy to describe in the model.

The dynamics of snow water equivalent was overestimated in the model compared to the measured values (Figure 6, Table 8). However, there were only a few measured values available from one winter (2006-2007).

Table 8. Mean absolute error, bias and mean measured range of simulated snow depth (cm) and snow water equivalent (mm) under situations of undisturbed snow accumulation (CTRL).

Variable	Treatment	Mean absolute error	Bias	Mean measured range
Snow depth (cm)	CTRL	9.39	6.81	4.46
Snow water equivalent (mm)	CTRL	35.38	35.38	14.60

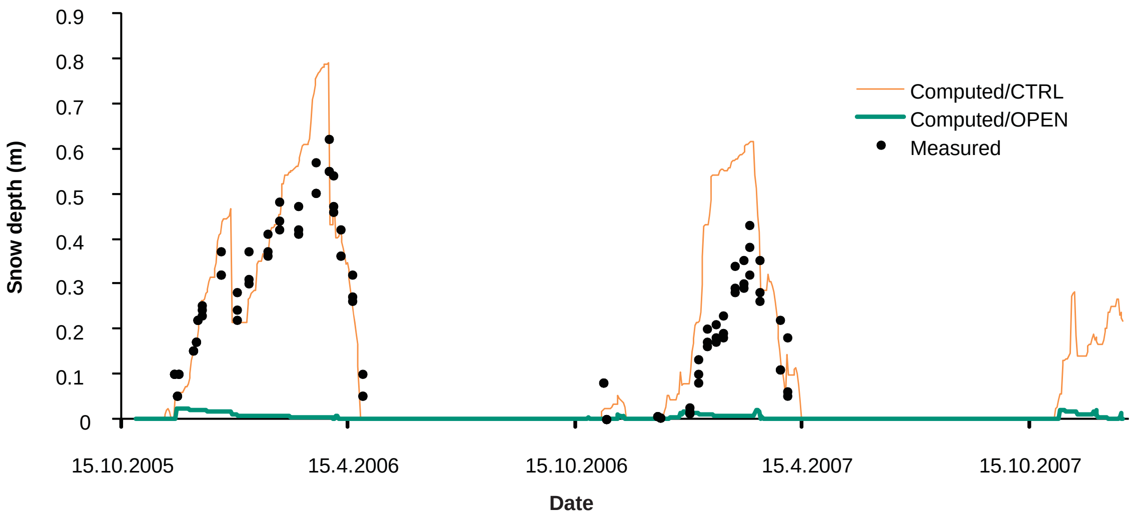


Figure 5. Simulated snow depth as a solid line and measured values as points under undisturbed snow accumulation (CTRL plots) and snow removed situation (OPEN plots).

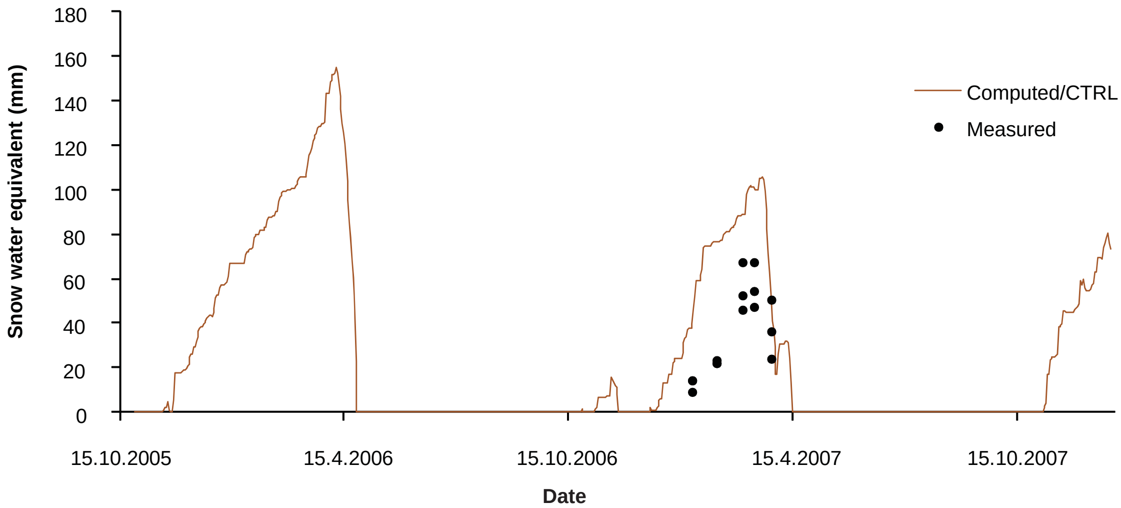


Figure 6. Simulated snow water equivalent as a solid line and measured values as points under undisturbed snow accumulation (CTRL plots).

The simulated frost depth showed some unrealistic frost depth values during the freezing and thawing periods (Figure 7). Firstly, the soil started to freeze abruptly (with about one day difference between the treatments) down to a depth of more than one meter. Thereafter the thawing process started from both above and below finishing with a sudden thaw. These rapid changes are likely to cause numerical instability in the model solution. Therefore, the model appeared to have problems predicting the freezing and thawing processes when the frost depth was rapidly increasing (notice the sudden changes appearing after 50 cm of depth) to the lower boundary of the modelled soil column. This may be due to difficulties in the interpretation of soil temperature differences or in the definition of water processes (see water balance section).

The differences between frost depths in situations with and without snow were not large. However, the freezing and thawing processes occurred slightly earlier when the snow was removed. In all cases, the difference between snow (CTRL) and snow-free (OPEN) conditions is more visible for soil temperature than for the frost depth, since soil is frozen at any temperature below 0 ^{o}C, i.e., the frost depth is only affected by temperature changes in the freezing point and it does not matter if the soil temperature changes in a colder range such as from -1 ^{o}C to -10 ^{o}C.

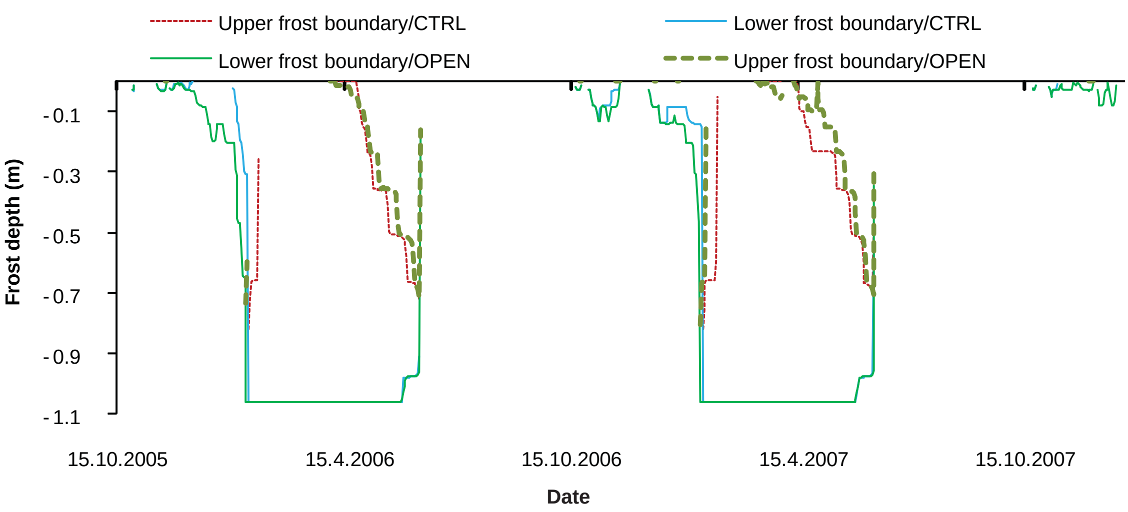


Figure 7. Simulated upper and lower boundaries of frost depth under undisturbed snow accumulation (CTRL plots) and snow removed situation (OPEN plots).

3. Water content

Figure 8 presents the simulated volumetric water content at different depths in undisturbed snow accumulation and snow removed situations. The soil moisture at all depths and in both treatments followed the same trend characterized by low soil moisture in winter (due to soil frost) and a slightly decreasing fluctuation in summer and autumn. The water content peaked in spring as a result of snowmelt, which was only seen in the case of snow accumulation conditions. While the water content at depths of 5 and 15 cm was similar, the water content at 50 cm increased by about 5 % and its fluctuation decreased. Thus, the low soil moisture values (due to soil frost in winter and transpiration in summer) were less common at the depth of 50 cm. Moreover, at this depth, the occurrence of low water content shifted over time from the 5 and 15 cm water contents due to retarded water percolation.

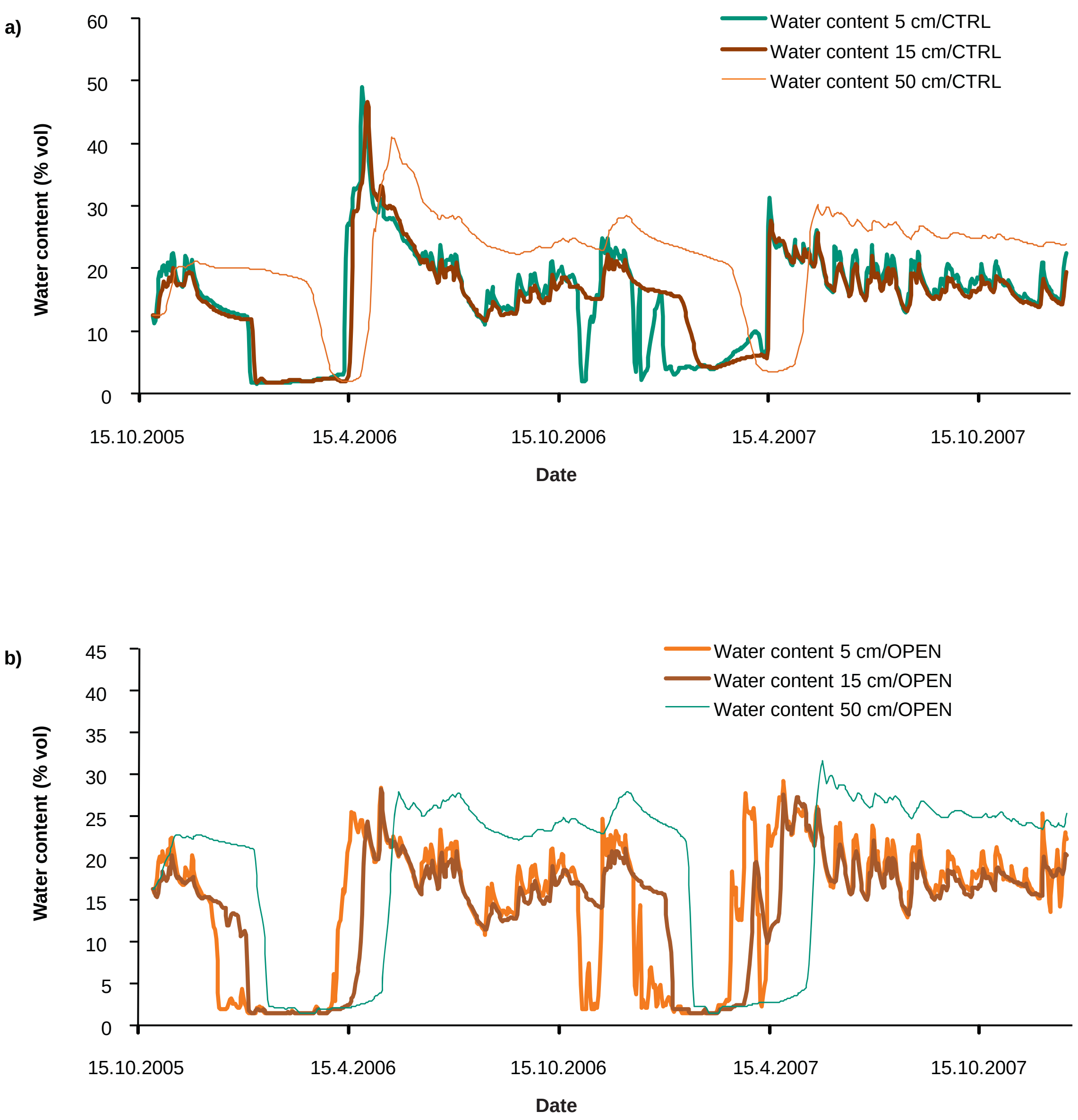


Figure 8. Simulated volumetric soil water content at 5, 15 and 50 cm of depth. a) Undisturbed snow accumulation (CTRL plots), and b) snow removed situation (OPEN plots).

At the depth of 15 cm, the differences between the CTRL and OPEN treatments were most visible during the first half of the year (from January until June) when the water content varies due to snowmelt patterns (Figure 9). The water content showed the same values in different treatments during the summer and autumn. At the time of the start of the snowmelt, in late winter 2006, the water content was lower in the plots with snow removed than in the plots with snow cover. Low water contents were found, especially during the winter of 2006-2007. The reason for the difference between treatments was possibly due to less accumulation of ice in the soil of the CTRL than OPEN treatment in winter as a result of the insulating capacity of snow on the CTRL, and the resulting higher soil temperature.

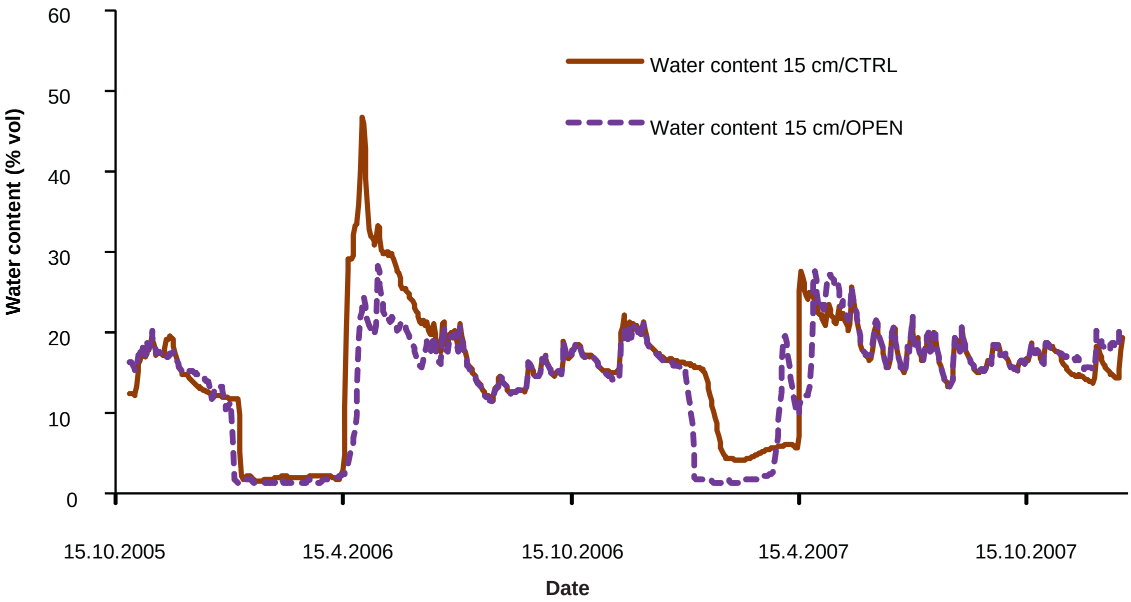


Figure 9. Simulated volumetric soil water content at 15 cm depth under undisturbed snow accumulation (CTRL) and snow removed situation (OPEN).

At first sight the simulations by the COUP model did not seem to represent well the water content processes at the depth of 15 cm since the differences between the modelled and measured values were large (Figure 10), in addition to the mean absolute error and bias being high (Table 9). However, the measured values had a large range of variability, being larger than the mean absolute error. Hence, this fact together with the realistic simulation of seasonal trends suggests that the COUP model simulations of water content were quite well calibrated.

The simulated soil water content is clearly overestimated during the summer and underestimated during the winter. This difference is likely to be related to flow domains and fraction of ice in the soil. In the present simulations the high flow domain dominated by macro pores was not considered, which could explain the rapid decrease of water content at the beginning of summer. In addition, we may assume that the simulations produced higher ice fraction in the soil than occurred at the sites.

Table 9. Mean absolute error, bias and mean measured range of simulated soil water content at 15 cm depth and for situations with and without snow cover (CTRL and OPEN respectively).

Depth	Treatment	Mean absolute error (% vol)	Bias (% vol)	Mean measured range (% vol)
15 cm depth	CTRL	5.37	-1.31	5.46
	OPEN	3.53	1.48	4.63

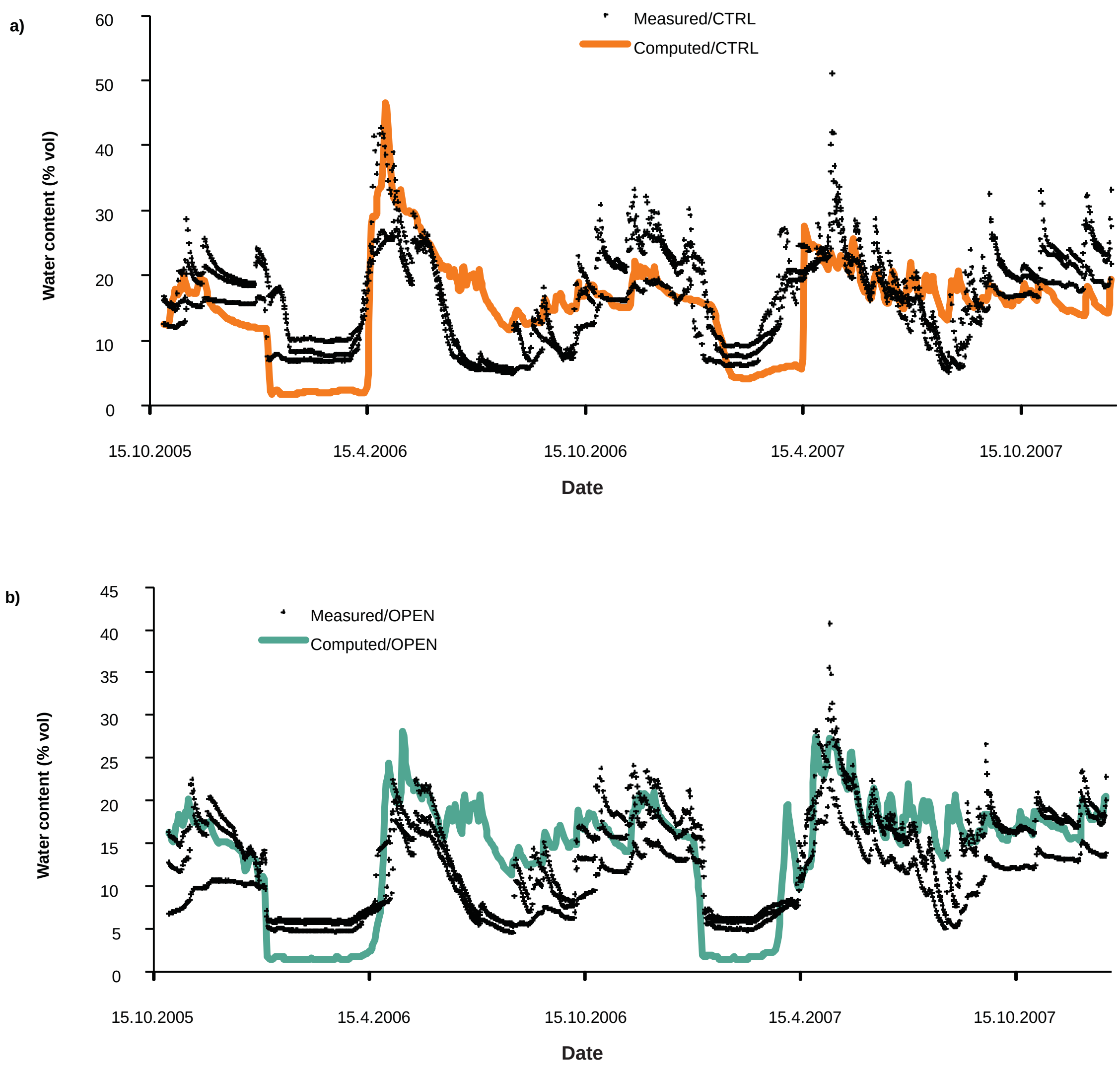


Figure 10. Simulated volumetric soil water content as a solid line and measured values as points on three replicate plots at the depth of 15 cm. a) Undisturbed snow accumulation (CTRL plots), and b) snow removed (OPEN plots).

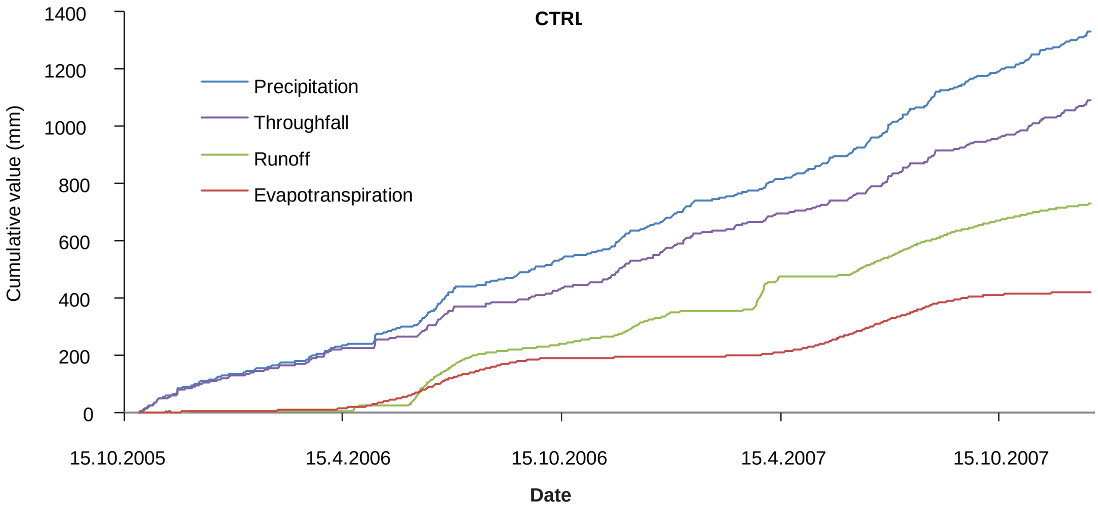
4. Water balance

The simulations presented in this work were not able to fully show consistent water balance (Table 10). The manual computation of the water balance showed errors of 153 and 33 mm for the snow and no snow conditions, respectively. The model also produced the water balance as an output defined as the sum of the inflows subtracted by the outflows and the difference in water storage. Although ultimately this value should be zero, the accumulated water balance for the whole period was 80.53 mm under undisturbed snow situations (CTRL) (daily max. 11.57 mm and daily min. -7.74 mm) and 28.40 mm when the snow was removed (OPEN) (daily max. 2.32 mm and daily min. -3.36 mm) resulting in an excess of water input in the water balance. Since the values were higher under undisturbed snow situations the problem can partly be related to the snow simulation. In addition, the errors in the model calibration must be considered as another causal factor.

Table 10. Mass water balance error as the difference between precipitation and the sum of evapotranspiration, runoff and storage change throughout the simulation period.

Water balance (mm)	CTRL	OPEN
Precipitation (input)	1331.72	975.45
Evapotranspiration (output)	417.28	408.33
Runoff (output)	727.39	486.00
Storage change	-46.64	19.02
Mass balance error	153.16	33.70

a)



b)

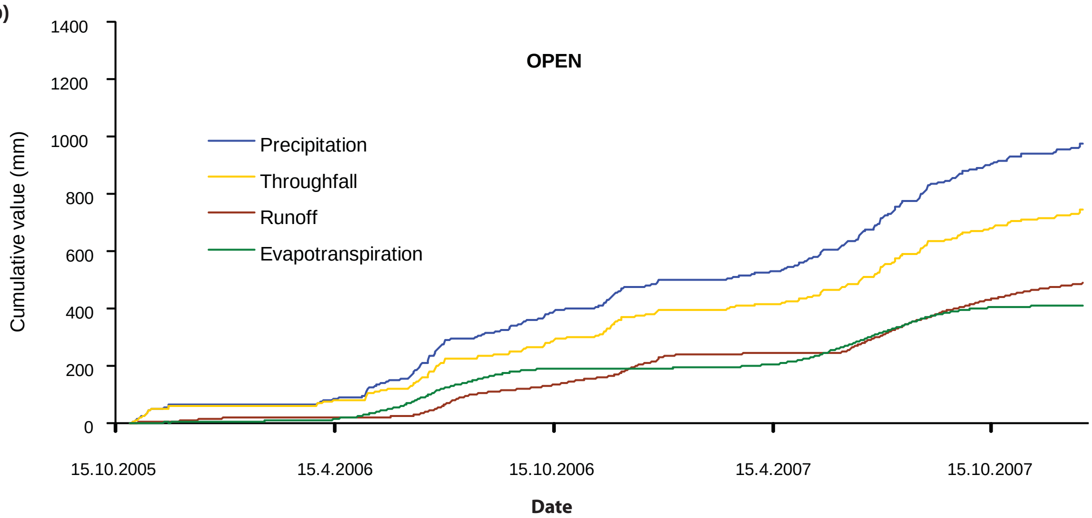


Figure 11. Representation of some balance components including cumulative values of precipitation and throughfall as inputs, and runoff and evapotranspiration as outputs. a) Undisturbed snow accumulation (CTRL plots), and b) snow removed (OPEN plots).

Figure 11 shows the cumulative water balance components as a function of time in terms of accumulated precipitation, throughfall, runoff, and evapotranspiration. Firstly, a considerable decrease in precipitation, throughfall and runoff is seen when the snow was removed compared to the undisturbed snowfall situation. On the other hand, while the accumulation of precipitation, throughfall and runoff depended on the plot type (CTRL or OPEN), evapotranspiration showed similar accumulation for both situations during the growing season, which was not affected by the snow removal.

Discussion

The COUP model reproduced reasonably well the daily variation of soil temperature at different depths as well as the depth of snow cover. The model was capable of describing the typical effects of the snow as an insulator on soil temperature. Moreover, although the soil temperature was slightly overestimated (less than 1 ºC), the simulated soil temperatures agreed well with the measured ones especially when undisturbed snow cover was considered. However, this agreement became poorer in deeper soil depths. In order to solve this mismatch, on one side, the results can be improved by calibration of the model, as well as by increasing the soil profile depth in the computation domain. Moreover, it could be useful to separately simulate the temperature during summer and winter since, in the cases of snow removed, the high underestimation in winter and the overestimation in summer were masked in the assessment of long term results over several seasons. On the other side, the model results can also be improved by the temperature measurements through collecting more data from different soil depths.

The snow cover result also showed quite reasonable comparison between simulated and measured values. However, the precipitation data were not representative enough, which affected the model's output, and consequently changed the calibration of the model. This was illustrated by an overestimation of snow depth (more evident the winter of 2006-2007) which influenced the water balance at the same time. Therefore, it is essential to have meteorological data from the vicinity of the experimental area.

The COUP model was capable of reproducing the typical effects of freezing and thawing on water content, i.e. decreased soil moisture in winter (due to soil frost), slightly decreased soil moisture fluctuation in summer and autumn, and a soil moisture peak in spring (due to melting processes) that occurred under snow cover situations. At the same time, the simulations correlated quite well with the measurements since the absolute errors and measured ranges were similar. However, the simulations presented considerable soil moisture overestimation during the summer and underestimations during the winter. The cause of which appeared to be related to flow domains, as well as the fraction of ice in the soil. A new consideration of flow domains (inclusion of macro pores in the model) and a new parameterization of the soil ice fraction calculations can improve the results. As in soil temperature, separate simulations of winter and summer periods can be useful to more accurately define the model conditions.

Some simulated outputs produced by the calibrated model, i.e. frost depth and water balance outputs, were not fully consistent. The frost depth results showed that the model had difficulties in predicting thawing and freezing processes at times when the frost depth rapidly increased (showing sudden unrealistic changes). This can be due to difficulties in the interpretation of soil temperature or in the definition of water processes. However, the development of simulations in a deeper soil profile can help identify the problem. The water balance printout of the model, as well as the manual mass balance check, indicated that there was an excess of water input in the model leading to a mass balance error. The misrepresentative precipitation data or possible errors in the definition of water conditions can be the cause of the error. The calculation of water distribution in each part of the system (plants and soil) separately can be useful to determine the reasons for this excess water. However, the trend of most variables regarding water balance appeared to be quite realistic.

Conclusions

In general, the COUP model simulations were able to illustrate the typical effects of freezing and thawing in terms of soil temperature, snow cover and water content. Moreover, the model was capable of defining undisturbed snow situations (CTRL plots) as well as artificial ones (OPEN plots) obtaining a good comparison with measurements in both cases. However, the simulated outputs such as frost depth and water balance had some deficiencies in their predictions. One problem was caused by the meteorological input data: Values such as precipitation or humidity were not well representative of the study area which introduced difficulties in the simulations. New meteorological data closer to the site would be valuable in improving simulations. If, in addition, net radiation and cloudiness were included in the data the model would be more precise and give better results. Another problem was related to the number of measurements characterising the spatial variation in the soil. There are a few data points in different depths and the values for each plot are too different between each other (spatial differences). More measurement points could improve the simulations. On the other hand, the data meets the model input requirements quite well. The minimum parameters that the model needs to run can be readily determined and it is easy to introduce them in the model. In addition to the data, the simulations can be improved, on one side, through applying changes in calibration process as suggested in the discussion and/or, on the other side, through validating the model with the use of new data (similar to the present data but not used in the model calibration) from the experimental station. Finally, despite a few weak points, the COUP model is a functional tool for the simulation of heat and water soil processes. It is easy to manage, well organized and capable of simulating a lot of soil scenarios by defining a few parameters and conditions, only.

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