Evaluation of land surface scheme SABAE-HW in simulating snow depth, soil temperature, and soil moisture within the BOREAS site, Saskatchewan

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Abstract

SABAE-HW is a multilayered version of the Canadian land surface scheme (CLASS). It is a one dimensional physically-based model that was adopted from a previous version of CLASS (2.6). SABAE provides an improved interface for groundwater modeling to simulate soil moisture, soil temperature, energy fluxes and snow depth for a wide range of soil and vegetation. This paper reports the first field comparison of SABAE-HW using an extensive ten-year data set from BOREAS (Boreal Ecosystem Atmosphere Study) and BERMS (Boreal Ecosystem Research and Monitoring Sites) project which is an area rich in terms of hydrology and meteorology data in central Saskatchewan, Canada. The model is also independently tested and verified with SHAW, an unsaturated zone transport model. Two boundary conditions are considered at the bottom of soil profile: water boundary condition and unit gradient boundary condition. Comparing the results of simulations and observed data showed substantial agreement in terms of snow depth and soil temperature. Snow depth and soil temperature were simulated reasonably well by SABAE with correlation value of 0.96 and 0.98, respectively. However there were some discrepancies for simulated soil temperature in winter. A general agreement was obtained in terms of unfrozen soil moisture results, especially in deeper depths but there were general similarities in observed and simulated soil moisture trends in winter. An average correlation value of 0.55 was found for SABAE while SHAW presented very small value (less than 0.30), which indicates a better fit between simulated and field data by SABAE. Although a unit gradient boundary condition does not influence soil moisture, it was found that unit gradient boundary runs resulted in increased bias towards overestimation of the soil temperature. Thus, a safer and more accurate approach, we believe, is to adopt a first type boundary (i.e. water table) condition at the bottom of the domain. This has implications for climate and weather modeling in general. The result of this field testing demonstrated the potential and high accuracy of SABAE-HW as a Canadian model capable of simulating snow depth, snow temperature, soil moisture, energy fluxes and so on and we believe is now appropriate to include this land surface scheme with its counterparts.

Introduction

In considering drought, a tightly coupled land surface scheme (LSS) and groundwater model needs to be developed. The methodology necessary for developing these models has only been recently explored. Dr. John Sykes (Jrykama, et al., 2002) and his team found that use of a simple hydrologic model to produce spatially varied groundwater recharge patterns, significantly improved groundwater simulations. We intended to build on this approach by using a detailed LSS in place of a simple hydrology. This is justified since LSSs have been designed as components of GCMs and are better equipped to deal with increased variability and shifts in mean conditions that are expected under climate change scenarios including drought. Tight coupling of these models will be required to simulate the impact of simultaneous irrigation/recharge on surface energy/water conditions and on groundwater potentiometeric surfaces. Developments with respect to a new lower boundary in a soil column are crucial to allow land surface schemes to be tied to groundwater models.

Of critical importance in these schemes is the accuracy by which fluxes to the atmosphere are simulated; this includes latent and sensible energy fluxes. Also, understanding and predicting soil moisture and soil temperature in porous media is also of importance in the environment sciences and engineering, especially in cold regions hydrology. The effects are many and include physical, chemical, and biological processes such as soil respiration, evapotranspiration, nitrification, and denitrificationSoil moisture and soil temperature are the most crucial variables to control the variation of CO_2 flux from the surface and soil respiration within the soil. Strong correlation has also been reported between these variables and soil respiration (Fang, C., Moncrieff, J. B. 1999, Tang et al., 2006). Note that because of their effects on microbial activity, soil water and temperature are the important factors that control seasonal variations in mineralization of soil organic matter. In addition, the relative importance of the physical, chemical and biological processes highly depend on soil moisture and snow depth. Thus, changes in soil moisture and soil temperature can affect the rate of ammonium and nitrate concentration below the surface (Freppaz et al., 2006). At this point in time, many soil-water-plant models such as SABAE-HW (Loukili et al., 2008), CLASS (Verseghy, 1990 and 1993), COUP (Jansson and Karlberg, 2001), HYDRUS 1D/2D (Simunek et.al 1999, and 2008), and SHAW (Flerchinger, 2000) have been developed to simulate water content and heat transfer under special conditions such as freezing and thawing, varied vegetation and solute transport. Each of these models has unique features and simplifications to solve for fluid, flow heat transport and so on, depending on their applications. However, these codes are sometimes difficult to verify, at least in field environments and practical applications, because many input parameters required. Thus, evaluating the conceptual models implicit in each code under field conditions is a major and complex research challenge.

For example, SABAE-HW (Loukili et al., 2008) is a multilayered version of the Canadian Land surface scheme (CLASS 2.6). It is a one dimensional, physically-based model that was developed to simulate soil moisture, soil temperature and snow depth for a wide range of soil and vegetation. The model also considers the effects of soil freezing and thawing on soil water dynamics. This paper reports the first field comparison of SABAE-HW using an extensive ten year data set from BOREAS (Boreal Ecosystem Atmosphere Study) and BERMS (Boreal Ecosystem Research and Monitoring Sites) which is a rich area in terms of hydrology and meteorology data in central Saskatchewan, Canada. SABAE-HW is also inter-compared and tested with the result of the SHAW model which is a vertical, one dimensional code with a detailed energy balance-based scheme (Flerchinger and Saxton, 1989). Although it was reported that SHAW generally overestimated evaporation and underestimated water storage, and drainage, we chose this code for the comparison because it is a well known and includes snow accumulation and evapotranspiration from multispecies plant canopy (Loukili et al., 2008). SHAW’s application has been extensively verified (Flerchinger, 1991, Flercginger et al., 1996, Link et al., 2004, Xiao et al., 2006).

In the recent years, several models have been evaluated with the BOREAS project data. Levin and Knox (1997) developed a frozen soil temperature code (FroST) to simulate soil moisture and heat flux. The model was applied to Old Jack Pine (OJP) and Black Spruce (BS) field data at the BOREAS northern and southern studies area. The predicted snow depth results showed a qualitatively good fit with measured data, whereas predicted soil temperature results were underestimated comparing to the measured data. Moreover, there were large differences between the simulated results and observed data when snow was present. Differences of about 50 percent were observed between simulated (snow depth and soil temperature) and measured data in winter. Two different versions of CLASS, the Canadian Land Surface Scheme (2.7 and 3.0), were also tested and verified by the OJP site data (Bartlet et al., 2002) Although Class 3.0 had been modified and updated in terms of canopy resistance, mixed precipitation, snow density and snow interception, both of these codes underestimated the snow depth and soil temperature values, but more so by CLASS 2.7. Furthermore, the 1998-2003 data for the BOREAS project was used to calibrate a forest hydrology model (ForHyM) which was able to simulate all major water and heat fluxes in a forest ecosystem. By entering daily weather and soil parameters as the input file, the code calculated soil moisture, soil temperature and frost depth at any depth. The code had been designed to consider the canopy closure, ground cover and forest floor depth. In spite of the satisfactory agreement between observed and calculated values in terms of snow depth, the simulated soil water content was not in a good agreement with measured data. Soil moisture was underestimated in winter and overestimated in summer. Simulated soil temperature results were also reported in a good fit during summer but there were some differences with observed data at winter time (Balland et al. 2006).

In addition to these model verification efforts, a few statistical studies were also carried out to show the relationships between landscape mean snow depth and fixed point snow depth in the BOREAS field sites. As has been reported, single, fixed-point measures of snow did not adequately represent the average snow depth at this site. Once empirical relationships were found between the fixed point depth and snow surveys for the accumulation season, it was recommended to consider scaling factors to improve the interpretation of the fixed point measurements in order to model the snow depth. These factors should be employed to increase confidence in the use of snow measurements at OJP site for modeling and climate variability changes. High correlation coefficient value (0.98) was found when a simple linear relationship was applied between fixed point and landscape mean depths at OJP site (Neumann et al., 2004 and 2006).

The purpose of this current paper is to evaluate the performance of SABAE-HW model by comparing predicted variables such as soil moisture, temperature and so on from the BOREAS field site. We will do this by driving the simulator with measured meteorological data over an extensive 10 year period. Calibration will be minimal, as most parameters are taken from default code values and publications (Table1). We believe that the SABAE code has now been verified and can be used for the simulation of fundamental variables of soil physics under different vegetations and freeze and thaw events. Also, future development of SABAE-HW will include coupling with nutrient transport equations to control nitrate transport at the field scale and subsequently to be used to assess a variety of BMPs (Best Management Practice) aimed at minimizing nitrate leaching to ground water under actual atmospheric and field conditions.

Methodology

Conceptual Model description

As mentioned, SABAE-HW (Soil Atmosphere Boundary, Accurate Evaluations of Heat and Water) is a soil multilayer version of the Canadian Land Surface Scheme (CLASS2.6). SABAE is also physically-based model that was adopted from CLASS 2.6 to provide an improved interface for groundwater modeling to calculate soil, heat and moisture transfer with a user-specified refined mesh. The general minimal residual (GMRES) iterative algorithm was implemented to solve soil heat flux terms. SABAE-HW requires three extensive input files: atmospheric, vegetation, and soil characteristic files. Half-hourly atmospheric inputs are: short wave radiation, long wave radiation, precipitation, surface temperature, wind speed, air pressure and specific humidity. Precipitation is considered as the snow precipitation when the air temperature is less than zero. The code has been designed for four different vegetation types: needleaf, broadleaf, crops, and grass. Two lower boundary conditions are applied: a water table and unit gradient boundary conditions. The first condition determines the water surface in groundwater and the second one represents a free drainage at the bottom of soil column. Atmospheric conditions above the upper boundary condition and soil condition at the lower boundary define heat and water fluxes in to the system. Subsequently, SABAE-HW calculates daily and half-hourly soil moisture (frozen and unfrozen), soil temperature, snow pack depth, evaporation, surface energy balance (sensible and latent heat flux), and net radiation.

Site description

The performance of SABAE-HW was evaluated using a 10 year (1997-2006) measurement stream from one of the Southern study areas of the BOREAS project, namely the Old Jack Pine site (OJP). This site is a mature forest with jack pine trees ranging in height from 12-15 m located in central Canada, Saskatchewan (53.916 N, -104.692W; Elev. 579). The mean annual precipitation is 467.2 mm and the mean annual air temperature is 0.4 ºC (1971-2000 Waskesiu normals). The soil type is sand with a well drained soil texture. The vegetation ground cover is mostly mature jack pine with a sparse green alder (Alnus crispa), predominantly lichen ground cover (Bernier et al. 2006). This kind of ground cover type provides thermal insulation to the soil in summer and since it is permeated by snow, it essentially becomes a part of snow pack in winter.

Instruments

The snow depth at OJP is measured using a SR50 sensor from Campbell Scientific. There are two of these sensors at OJP; one located in a clearing canopy and another located under the forest canopy. A Canadian snow sampler was also used to measure accumulative snow depth and provided data on integrated snow density and snow water equivalent (Forrest and Knapp, 2000). Soil moisture data were measured using CS615 probes from Campbell Scientific. At the OJP, the first two probes (0-15 and 15-30cm) were installed at a 45 degree angle (for higher resolution). The probes give a layer moisture average for each 15cm and the CS615 probes are 30cm long. Therefore when measuring a 15cm layer, higher resolution will be obtained than when measuring a 30cm layer. The deeper probes are installed at 30cm intervals and also give a layer average (30-60 and 90-120cm). The measurements were reported 6 times in a day at those described ranges. Soil temperatures were also measured by use of a Cu-Co thermocouple sensor made by Queens University (BOREAS/BERMS reports). It is basically a rod that is inserted in to the soil with thermocouples mounted at known intervals (2, 5, 10, 20, 50, and 100cm). Soil temperature, like atmospheric data, was monitored every 30 minutes (Keshta, et al., 2010)

Model evaluation and hydrological parameters

SABAE-HW was compared against measured data at OJP site over the period 1997 to 2006. Since the code has been developed for Δt=30min, we had a great source of data to assess the performance of SABAE. The code requires three input files: atmospheric, vegetation, and soil type files. Half-hourly atmospheric inputs include short wave radiation, long wave radiation, precipitation, surface temperature, wind speed, air pressure and specific humidity. Since the vegetation type of the field site is dominated by jack pine, they were classified as a needleaf in the model. To determine the soil moisture characteristics, SABAE used the formulas suggested by Clapp and Hornberger (1978):

$$\psi(\theta) = \psi_s \left(\frac{\theta}{\theta_s}\right)^{-b}$$

$$K(\theta) = K_s \left(\frac{\theta}{\theta_s}\right)^{2b+3}$$

Where ψ_s is the soil water suction at $\theta=\theta_s$, K_s is the soil hydraulic conductivity, θ is the soil moisture, θ_s is the soil moisture at saturation point (pore volume fraction) and b is an empirical constant. Soil parameters such as saturated hydraulic conductivity and pore volume fraction were specified from observation data. Unfortunately, there were no Clapp and Hornberger soil moisture constants available for the OJP site. Thus, the parameters b and ψ_s were determined by finding the best match between Clapp and Hornberger and van Genuchten soil characteristic curves as all soil parameters in van Genuchten formula had been reported for OJP site (Kuchment et al., 2006a). All the model parameters used for SABAE and SHAW model are listed in Table 1.

Two approaches were adopted for imposing the boundary condition at the bottom of the domain. The first approach was to apply unit gradient boundary to the bottom of the grid. Thus, the total depth of soil column was 3 meters (11 layers). In the second approach, since the water table is near a depth of 7 meters, the soil column was extended to 7 meters (19 layers) to fix the water table boundary condition at the bottom of soil column. In both cases, the two first layers have a thickness of 15cm, with 30cm and 40cm for the rest of layers (Figure 1). Furthermore, based on the observed data (soil moisture and soil temperature), the fixed point (Dirichlet condition) was used for upper boundary condition. The exact value of observed soil moisture and soil temperature data at t=0 (first time step) was applied for initial conditions at the middle of each layer. In the case of a water table boundary condition, initial soil moisture was set to a value of porosity at the bottom of the soil profile. Leaf area indices, visible albedo, near infrared albedo, vegetation rooting depth and canopy mass used in simulating hydrological processes of the site were based on the publications and also Old Jack Pine site in the northern study area of Manitoba (Bartlett et al., 2002 and Kuchment et al., 2006b). It is noted that soil temperature and soil moisture both are calculated at the midpoint of each layer. To obtain a reasonable result of calculated parameters in winter time, the model was initialized to observed values on August 1, 1997. It is important to mention that the same scheme was adopted for SHAW model regarding the number of layers and boundary conditions.

The Average Error (AE), the Root Mean Square Error (RMSE), and correlation coefficient (r) are computed to compare simulated variables to the field data (Bruijn et al., 2009). The average error demonstrates how well the simulated data approximates the field data, either being above or below measured values, whereas the root mean square error is a measurement for the variation between datasets. The closer the calculated values are to zero, the better approximation of simulated to the field data. However, the best approximation is achieved when correlation coefficients are close to one. These performance measures, used for comparing model predictions to observations, are calculated as:

$$AE = \frac{(\sum_{i=1}^{n} S_i - O_i)}{n}$$

$$RMSE = \sqrt{\frac{(\sum_{i=1}^{n} S_i - O_i)^2}{n}}$$

$$r = \frac{(\sum_{i=1}^{n} O_i - \bar{O})(\sum_{i=1}^{n} S_i - \bar{S})}{\sqrt{(\sum_{i=1}^{n} O_i - \bar{O})^2 \, (\sum_{i=1}^{n} S_i - \bar{S})^2}}$$

Where S_i is the simulated value, O_i is the observed value, $\bar{S}$ and $\bar{O}$ are the mean of simulated and observed values, and n is the number of data point.

Results and Discussions

Snowpack

The result of simulated and measured snow depth over 10 years study at OJP site is given in Figure 2. Comparing the distribution of measured and SABAE snow depth shows a satisfactory agreement, especially during the period 2003-2006. Although SABAE simulated snow depths slightly lower than observed data (35 percent difference at winter 2002), there is a good correlation between two plots. The correlation coefficient value of 0.96 was found for the SABAE model. However, the SHAW model shows a different pattern when the snowpack is formed. In fact, snow depth increases drastically and then drops gradually sooner than SABAE compared to measured data. Figure 3 shows the plots of average error and root mean square error versus time for the SABAE and SHAW model with regard to the field data. Both SABAE plots show the closer values to zero. Furthermore, as detailed in Table 2, SABAE simulated the snow depths with higher correlation value than SHAW which is a good indication of SABAE in terms of simulation of snow depths.

Figure 2 also confirmed the results of snow depths modeled by CLASS and ForHyM model (Balland et.al 2006). Note that all three models underestimate the values of snow depth. However, FroST (Levin and Knox, 1997) overestimated snow depth results in winter 1994 at the OJP site. A 50 percent difference between measured and predicted snow depth has been observed in winter time. Variation in snow density over time and snow reflectance which was constant in the model has been reported as the reasons of these differences. In fact, the model assumed that snow density increases only if air temperatures are above zero while the density of actual snow varies as snow ages and compacts over time.

According to Neumann et al. (2006), at many of the BOREAS research sites, fixed point snow depth measurements cannot approximate the average landscape depth taken by the snow surveys. They strongly recommended that the adjustment factors should be employed for the snow fall to obtain the logical result in terms of hydrological and surface processes. In order to produce the best overall fit between simulated and measured snow depth, a snow correction factor of 1.4 has been applied to the precipitation data in winter.

Soil temperature

Figure 4 shows the simulated and measured soil temperatures with the water boundary condition at the bottom of the soil profile in four depths at OJP site. In general, there is a strong correlation between simulated soil temperatures (SABAE and SHAW) and measured data. However, there are differences during those times when a snow pack is present. Table 3 shows that the agreement between the simulations and observations was satisfactory during the summer of 2003 (June to September). High correlation coefficient values (0.92 to 0.98) were found for simulated soil temperatures, but as the air temperature drops after November, both simulated soil temperatures were underestimated in winter. The negative average error represents model's underestimation of the field data. As shown in Table 4, the average error reported for both models was negative. However, the SABAE error values were relatively close to zero, indicating SABAE was accurate in estimating soil temperatures in winter. Similar results were found during 10 years of study on OJP site. Although both SABAE and SHAW take into account the soil insulation, there is a discrepancy between measured and modeled soil temperatures in winter. In fact, the insulating effect of the snow does not allow for colder temperatures to penetrate the soil. Moreover, the vegetation cover which is permeated by snow enhances thermal insulation to the soil below. Thus, comparing to the predicted soil temperature, a significant rise in actual soil temperature is expected. As shown in Figure 4, the effects of soil insulation on simulated soil temperature decreases at a depth of 105cm. Decreasing the snow depth reduces the degree of insulation and results in cold soil temperatures. In addition, analysis indicates that SABAE layer reach much cooler temperatures than those simulated by SHAW and field observations and generate their ice content much sooner in winter. This might be related to a fixed minimum liquid soil moisture content from the parent model CLASS 2.6 that limits liquid soil moisture to 4%. Since SHAW is permitted to go lower, some additional energy loss may be consumed by the latent heat of fusion rather than cooling temperatures below the freezing temperature. Table 5 shows that although both SABAE and SHAW models have the same correlation coefficient (0.98), SABAE average error and root mean square error are closer to zero at lower depths than errors computed by SHAW. In spite of the fact that a strong correlation was found for both models at the deeper depths (105 cm), SHAW showed a smaller average error than SABAE model.

A comparison of simulated and measured values of soil temperature with the unit gradient boundary condition for the same period of 1997 to 2006 is given in Figure 4. Although the coefficients of correlation did not change for SHAW and SABAE model, both models showed larger errors with regards to the unit gradient boundary condition at the bottom of soil profile. In point of fact, soil temperatures are underestimated compared to predicted soil temperatures with a water boundary condition. The saturated lower boundary condition probably did not underestimate soil temperature as much because the increased water content raised the heat capacity and heat content of the soil layers, and with more water, there is more heat released when each layer freezes. Interestingly, as it is shown by Table 6, average errors and root mean square errors calculated for SHAW model are smaller than SABAE errors.

Soil moisture

Figure 6 compares the distribution of the simulated and measured unfrozen water content in the soil profile at OJP site with a water table boundary condition. As apparent from these figures, soil moisture correlations are not as good as snow depth and soil temperature distribution, especially in lower soil layers. The positive values of average error indicate that soil moisture is overestimated by both SABAE and SHAW (Table 7). As indicated by relatively small AE values (Table 7), model bias in predicting soil moisture was generally small. Over the simulated period, the average of AE values was 0.03 and 0.05 in SABAE and SHAW, respectively. However, the main disagreement between models and measurements is at greater depths, when both models gave a correlation of less than 0.25 for the depth of 90-120 cm. In addition, SABAE and SHAW did not present the similar correlation coefficient between simulated and measured for the top 90cm of the soil profile. An average value of 0.55 was found for SABAE while SHAW presented a small value (less than 0.30) in terms of correlation, which indicates a better fit between simulated and field data by SABAE. As it was shown in Figure 6, although both models underestimated unfrozen soil moisture in winter, small differences between simulated and observed soil moisture were found. Compared to observed soil moisture in winter, we found a difference of 0.01 and 0.04m^3m^{-3} for SABAE and SHAW model, respectively, which demonstrates the ability of SABAE to simulate unfrozen soil moisture in winter. However, relatively large differences (about 0.08m^3m^{-3}) were obtained in summer for both models, especially at deeper soil layers. These discrepancies might correspond to the points where the data were chosen. Since SABAE and SHAW computes the value of soil moisture at the middle of each layer, the results of simulated and observed data were compared at the depths of 7.5, 22.5, 75, and 105 cm. Unfortunately the exact value of observed data at these points had not been reported. As a matter of fact, each observed moisture is an average of 2 or more samples taken at 30cm intervals. Thus, the simulated soil moistures by SABAE and SHAW were calculated specifically for one point at the middle of each layer while the measured soil moistures are corresponding to the average of soil moisture in each layer. Also, the amount of underestimation of liquid water in the soil in winter is probably a result of the minimum possible value for liquid water, a model parameter. The actual soil moisture reading depends on soil organic matter, soil texture, and soil bulk density close to each sensor. Because of the coarse nature of the soil at the OJP site, water contents are always very low. It has been reported that even if two soil moisture probes are located at the same depth but different locations, it is unlikely to obtain the same soil moisture values (Balland et al., 2005). Moreover, there has been an attempt to improve calculations of soil moisture by decreasing the depths of soil layers. However, no significant improvement of the simulated results has been obtained.

Both codes calculate volumetric water content based on the initial soil moisture, and characteristics of soil texture including the percent of sand, silt, clay and organic matter. There are implicit default values such as soil saturation point, porosity, permanent wilting point and soil permeability all which affect soil moisture. Furthermore, SABAE-HW did not account for the amount of runoff, although this is likely to be very small. Also note that SHAW has been extensively tested, especially for soil moisture prediction and has been successfully verified. Figure 7 also compares calculated and measured soil temperatures with the unit gradient boundary condition. For the whole period of study, the unit gradient boundary does not influence the moisture of soil layers. Although the coefficient of correlation is slightly lower than the case presented the water boundary condition, the average error and root mean square error are still the same (Table 8).

Conclusions

SABAE–HW was field tested using 10 years of data from Old Jack Pine site at the Boreas central Saskatchewan field station, Canada. The field site consists primarily of sand with a high value of saturated hydraulic conductivity. The model was verified against measured data and compared with another well known code, SHAW. Snow depth, soil temperature and soil moisture were simulated and the model verified in this paper with regard to two boundary conditions at the bottom of soil profile: a water table boundary condition and unit gradient boundary condition. Comparing the results of simulations and observed data showed a satisfactory agreement in terms of snow depth and soil temperature. However, there were some discrepancies in terms of soil temperature in winter. A general agreement was not obtained in terms of unfrozen soil moisture results especially in lower depths but there were similarities in observed and simulated soil moisture trends, especially in winter. Although a unit gradient boundary condition does not influence soil moisture, the plots showed that unit gradient boundary runs resulted in more bias towards an overestimation of the soil temperature. Both models showed larger errors with regards to the unit gradient boundary condition at the bottom of soil profile while the coefficients of correlation did not change for SHAW and SABAE model. Thus, a safer and more accurate approach, we believe, is to adopt a first type boundary (i.e. water table) condition at the bottom of the domain. This has implications for climate and weather modeling in general.

The result of this field testing demonstrated the potential of SABAE-HW as a Canadian model capable of simulating snow depth, snow temperature and soil moisture to high accuracy. A more precise field testing of the model should be conducted later to further validate its application to simulate total and unfrozen soil moisture.

With this ability of SABAE-HW to model snow pack, soil temperature, and soil moisture, a nutrient transport module will now be coupled with SABAE to simulate nitrogen losses at different levels of soil profile. Moreover, SABAE-HW considers the effects of soil freezing and thawing on soil water dynamics. Since we found a good agreement between simulated and observed data in winter time, the idea of coupling SABAE with nitrogen transport model is under investigation, in order to simulate nitrate and ammonium concentration in presence of freezing and thawing activity.

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Table 1. A summary of SABAE-HW soil and vegetation inputs

parameters	values
% sand	95-99
%clay	1-5
Sand index	15
Clay index	1.4
Pore volume fraction(m^3/m^{-3})	0.4
Saturated soil water suction(m)	0.22
Saturated hydraulic conductivity(m/s)	16.8e-6
b	2.30
Canopy height(m)	13.5
Leaf area index(m^2/m^{-2})	1.9
Visible albedo	0.03
Near-infrared albedo	0.19
Root depth(m)	1

Sand index = min ((%sand-17)/5, 15) Clay index = min ((%clay+2)/5, 12)

Table 2. Average Error, Root Mean Square Error and Correlation values for simulated and measured snow depth within Old Jack Pine site from Sep. 1997 to Dec. 2006

Measured data versus SABAE			Measured data versus SHAW		
Average err	RMSE	Correlation	Average err	RMSE	Correlation
-0.007	0.04	0.96	-0.02	0.06	0.90

Table 3. Average Error, Root Mean Square Error and Correlation values for simulated and measured soil temperatures at various soil depths within Old Jack Pine site from Jun. 2003 to Sep. 2003 (Water boundary condition)

	Measured Data Versus SABAE			Measured Data Versus SHAW		
depth	Average err	RMSE	Correlation	Average err	RMSE	Correlation
7.5	0.60	1.88	0.92	-1.24	1.89	0.94
22.5	0.25	1.46	0.92	-1.38	1.75	0.94
50	-0.14	1.13	0.92	-1.51	1.71	0.95
100	-2.10	2.24	0.97	-2.65	2.70	0.98

Table 4. Average Error, Root Mean Square Error and Correlation values for simulated and measured soil temperatures at various soil depths within Old Jack Pine site from Nov. 2002 to Apr. 2003 (Water boundary condition)

	Measured data versus SABAE			Measured data versus SHAW		
depth	Average err	RMSE	Correlation	Average err	RMSE	Correlation
7.5	-1.69	2.29	0.93	-2.27	3.22	0.90
22.5	-1.75	2.24	0.92	-2.01	2.55	0.93
50	-1.99	2.40	0.91	-1.96	2.23	0.94
100	-1.37	1.54	0.97	-0.80	0.95	0.97

Table 5. Average Error, Root Mean Square Error and Correlation values for simulated and measured soil temperatures at various soil depths within Old Jack Pine site from Aug. 1997 to Dec. 2006 (Water boundary condition)

	Measured Data Versus SABAE			Measured Data Versus SHAW		
depth	Average err	RMSE	Correlation	Average err	RMSE	Correlation
7.5	-0.70	2.06	0.98	-1.06	1.97	0.97
22.5	-0.80	1.84	0.98	-1.03	1.67	0.97
50	-1.01	1.83	0.98	-1.00	1.49	0.98
100	-1.18	1.30	0.97	-0.85	1.34	0.98

Table 6. Average Error, Root Mean Square Error and Correlation values for simulated and measured soil temperatures at various soil depths within Old Jack Pine site from Aug. 1997 to Dec. 2006 (Unit gradient boundary condition)

	Measured Data Versus SABAE			Measured Data Versus SHAW		
depth	Average err	RMSE	Correlation	Average err	RMSE	Correlation
7.5	-1.36	2.92	0.97	-1.30	2.24	0.97
22.5	-1.51	2.69	0.97	-1.20	1.90	0.98
50	-1.68	2.65	0.97	-1.19	1.68	0.98
100	-1.86	2.45	0.95	-0.96	1.49	0.98

Table 7. Average Error, Root Mean Square Error and Correlation values for simulated and measured soil moisture at various soil depths within Old Jack Pine site from Aug. 1997 to Dec. 2006 (Water boundary condition)

	Measured data versus SABAE			Measured data versus SHAW		
depth	Average err	RMSE	Correlation	Average err	RMSE	Correlation
0-15	0.007	0.04	0.53	0.06	0.10	0.13
15-30	0.02	0.04	0.62	0.05	0.08	0.35
30-60	0.01	0.05	0.42	0.03	0.05	0.32
60-90	0.02	0.05	0.57	0.03	0.05	0.25
90-120	0.01	0.05	0.26	0.03	0.04	0.30
120-150	0.03	0.06	0.12	0.04	0.05	0.23

Table 8. Average Error, Root Mean Square Error and Correlation values for simulated and measured soil moisture at various soil depths within Old Jack Pine site from Aug. 1997 to Dec. 2006 (Unit gradient boundary condition)

	Measured data versus SABAE			Measured data versus SHAW		
depth	Average err	RMSE	Correlation	Average err	RMSE	Correlation
0-15	0.005	0.04	0.51	0.06	0.10	0.13
15-30	0.02	0.04	0.59	0.05	0.07	0.40
30-60	0.01	0.05	0.37	0.03	0.05	0.36
60-90	0.02	0.04	0.51	0.02	0.05	0.30
90-120	0.01	0.05	0.21	0.01	0.04	0.20
120-150	0.02	0.05	0.09	0.01	0.04	0.20

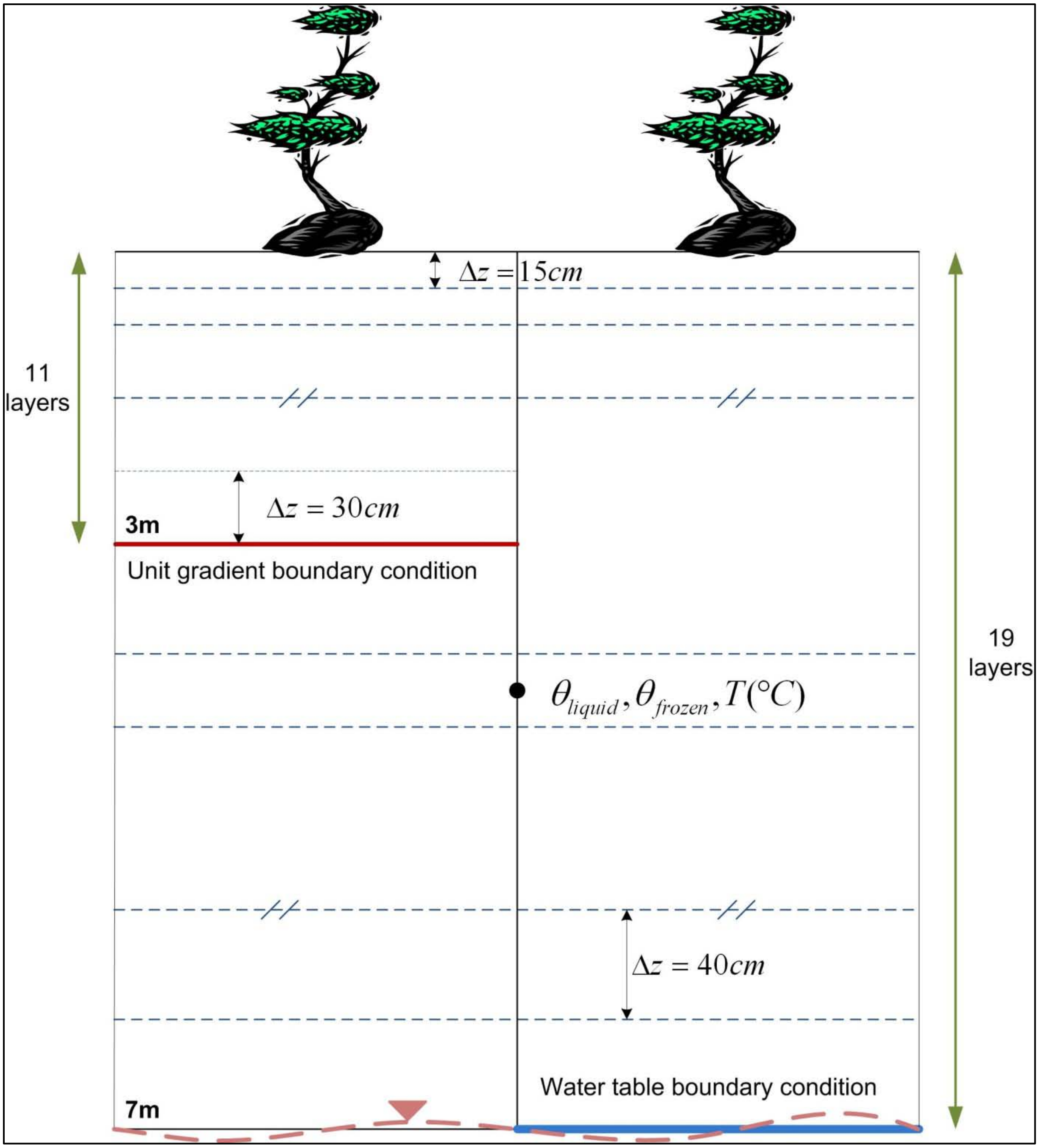

Fig 1. Overview of the lower boundary conditioins in SABAE-HW applied for the OJP site

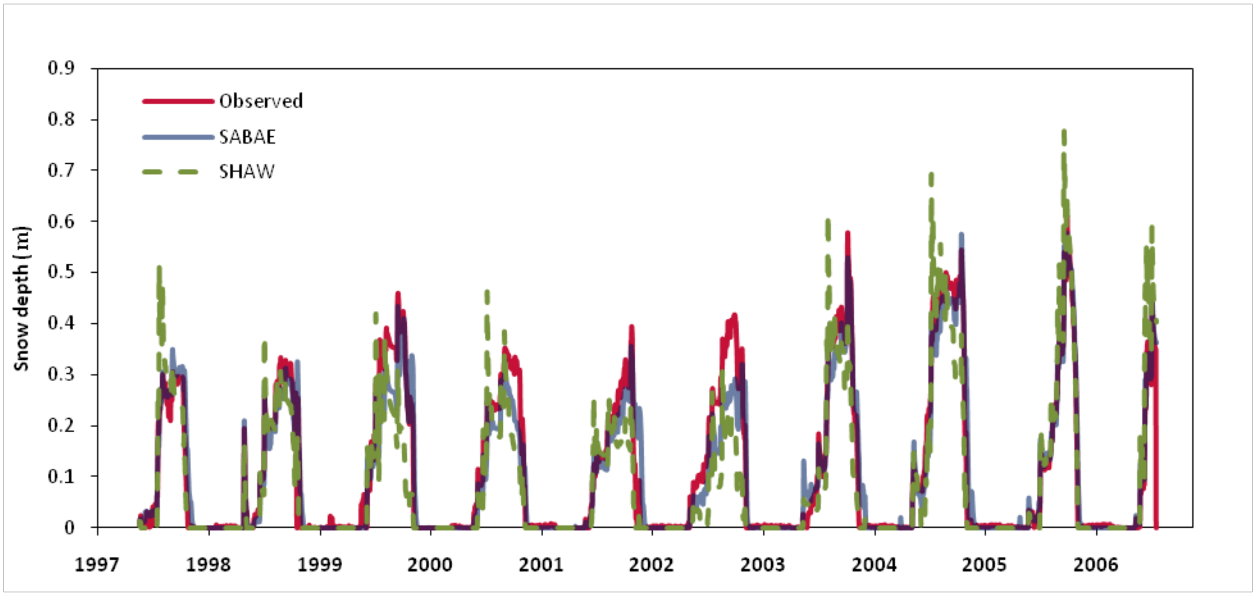

Fig 2. Simulated and measured snow depths Sep. 1997 to Dec. 2006

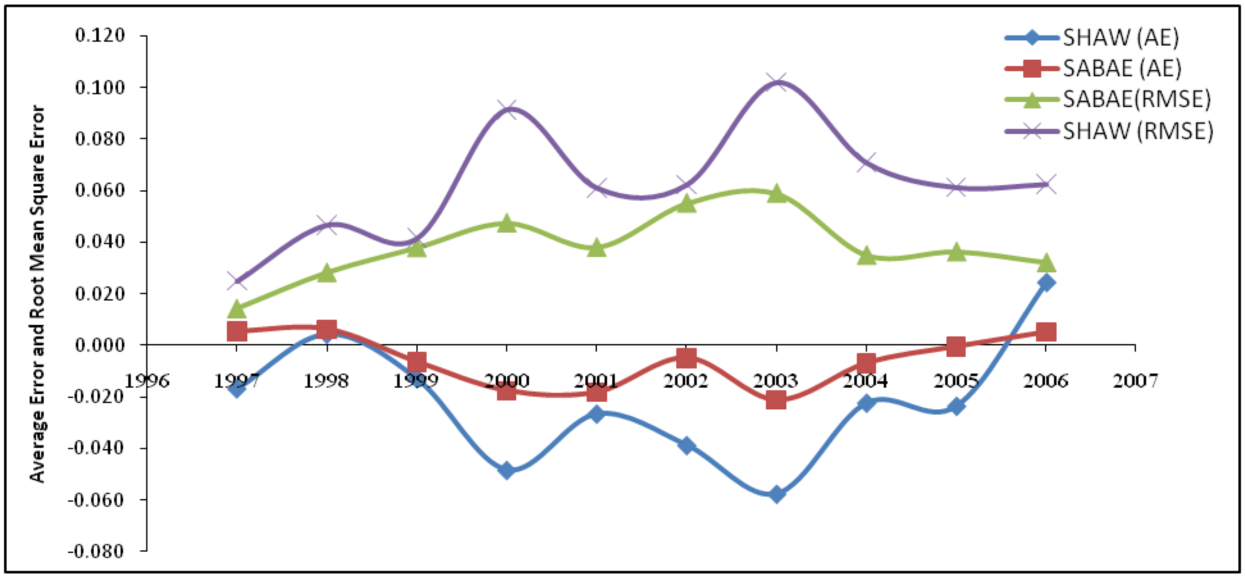

Fig.3. Average Error and Root Mean Square Error for SABAE and SHAW simulated snow depth from Sep. 1997 to Dec. 2006

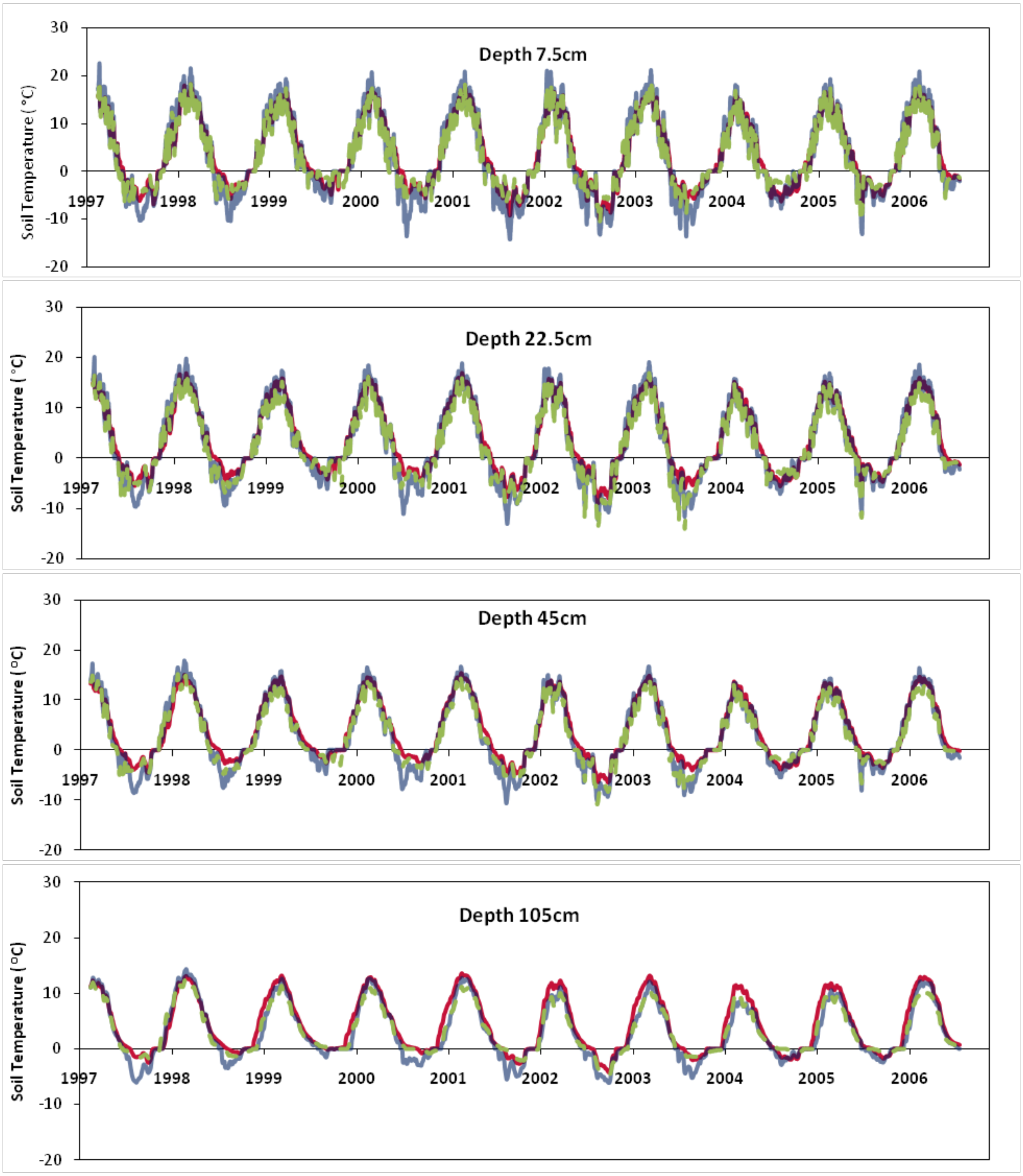

Fig 4. Simulated and measured soil temperatures 7.5, 22.5, 45 and 100 cm below the soil surface from Aug.1997 to Dec.2006 (Water boundary condition)

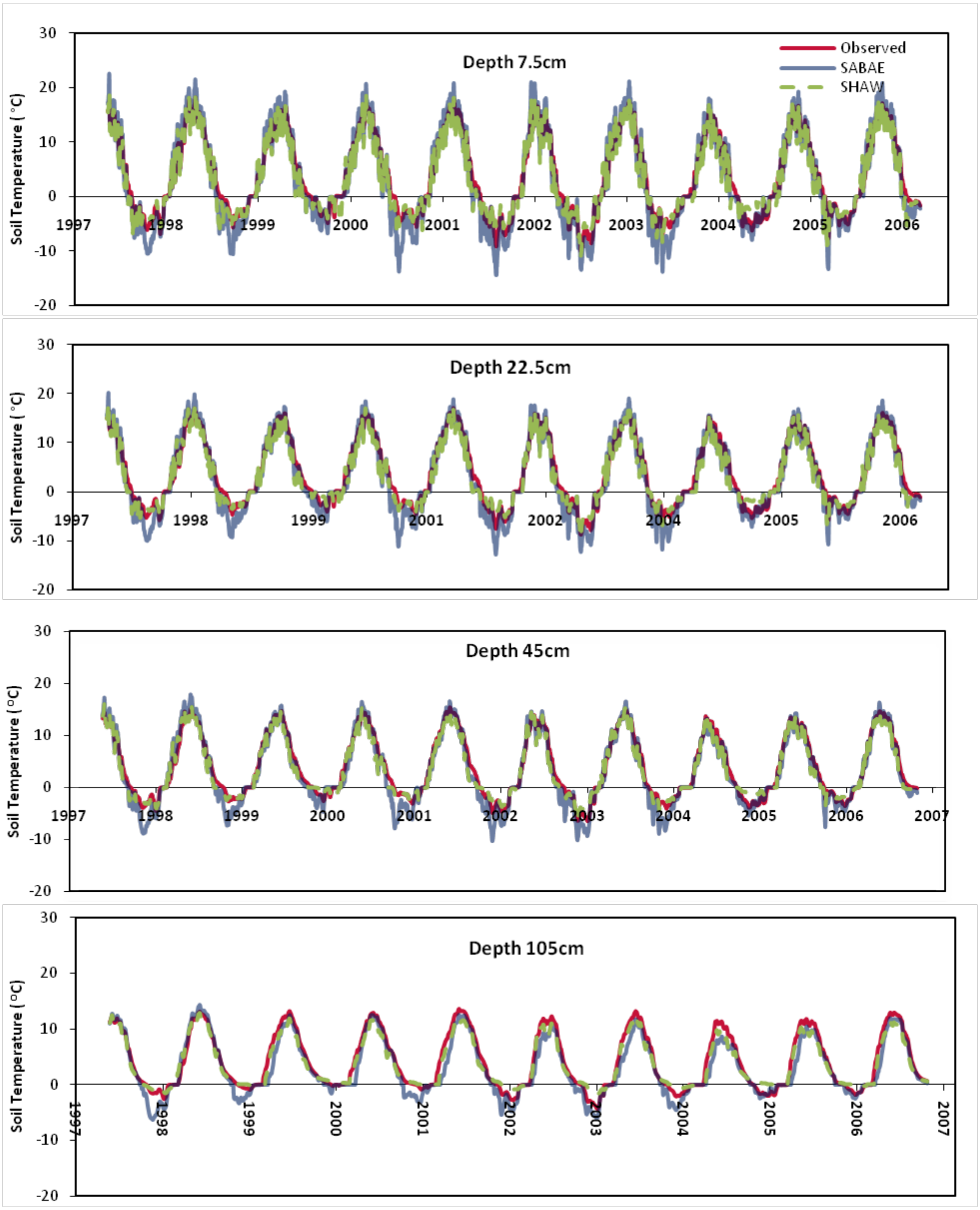

Fig 5. Simulated and measured soil temperatures 7.5, 22.5, 45 and 100 cm below the soil surface from Aug.1997 to Dec.2006 (Unit gradient boundary condition)

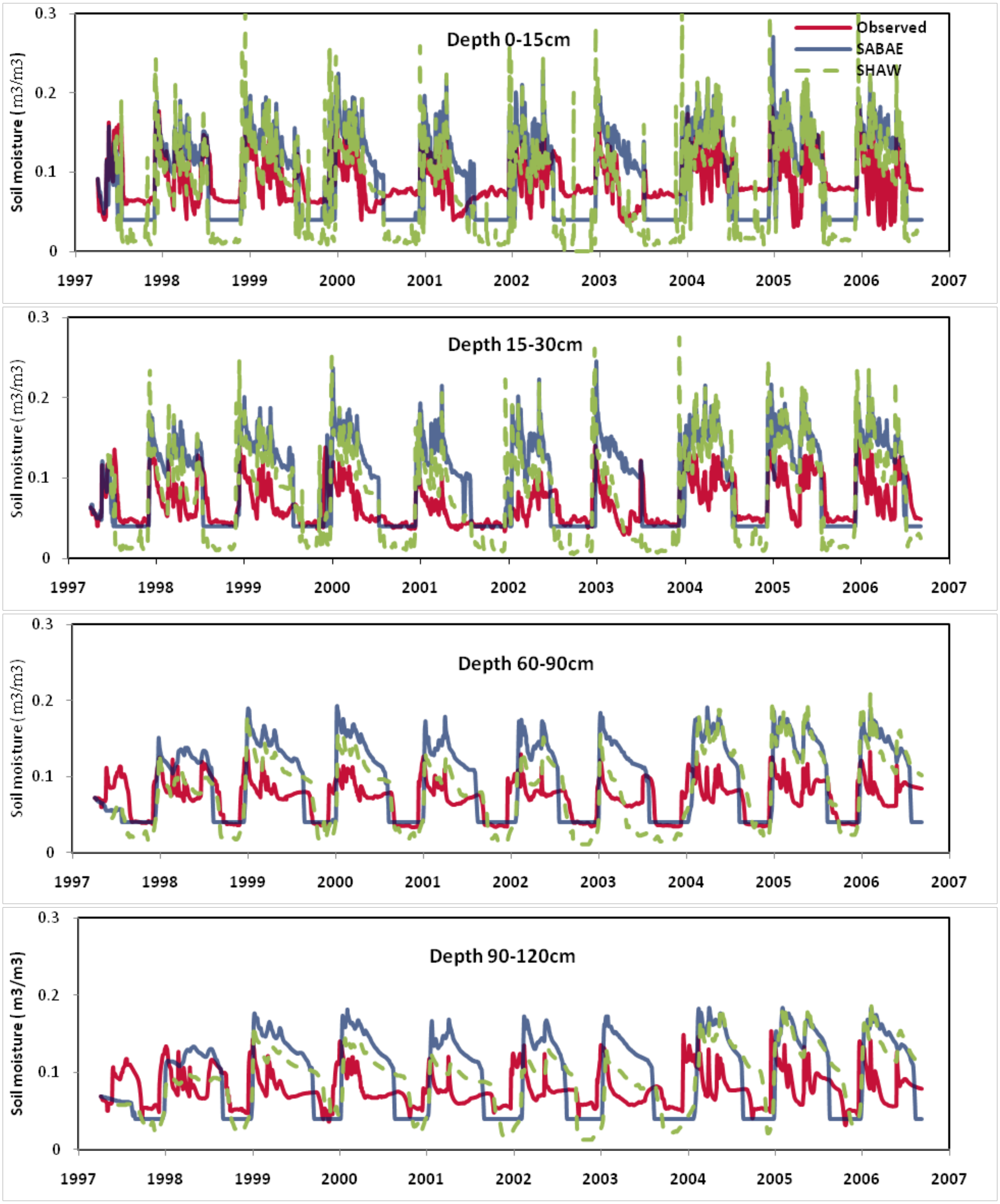

Fig 6. Simulated and measured soil moistures 7.5, 22.5, 45 and 105 cm below the soil surface from Aug. 1997 to Dec. 2006 (Water boundary condition)

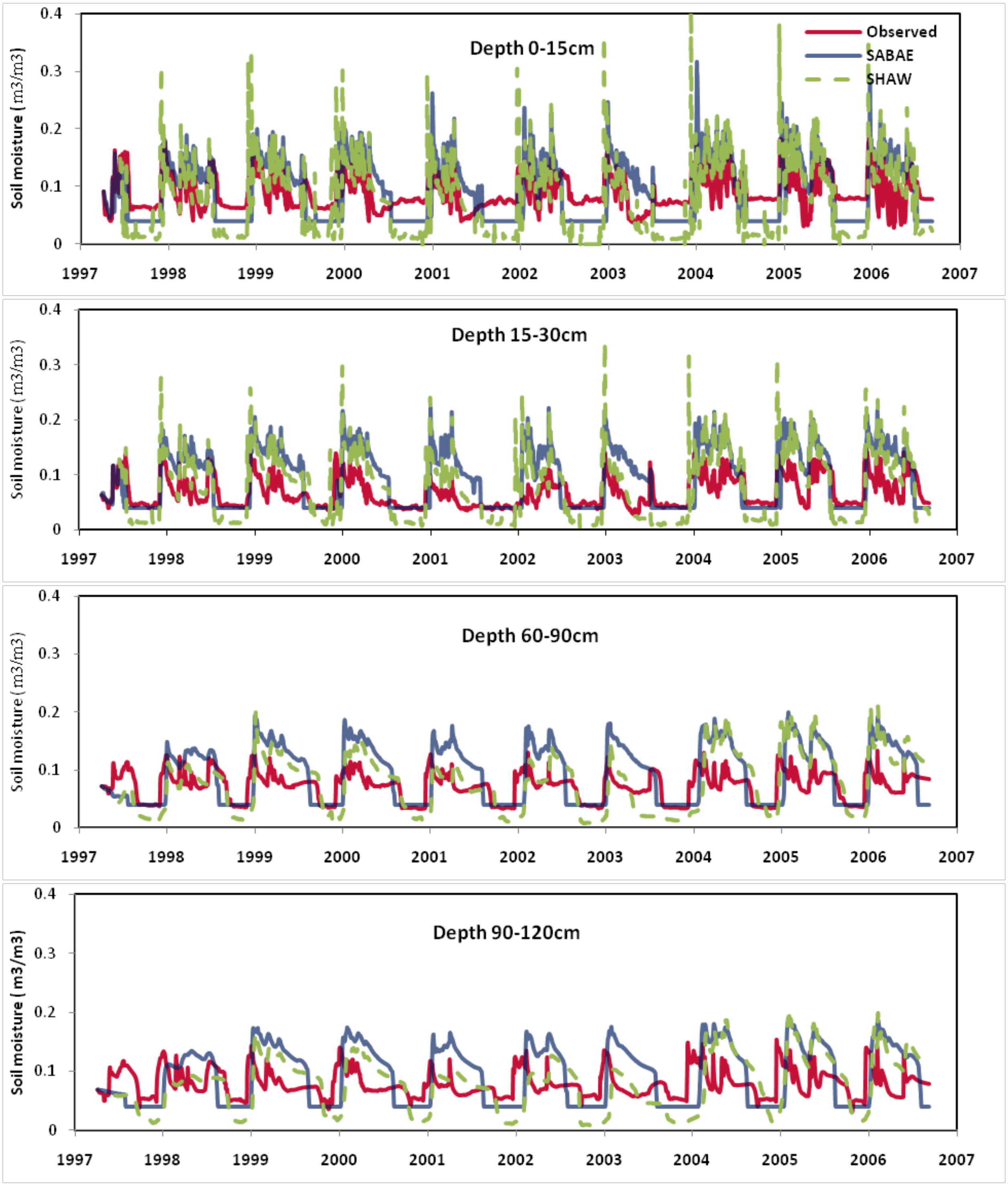

Fig 7. Simulated and measured soil moistures 7.5, 22.5, 45 and 105 cm below the soil surface from Aug. 1997 to Dec. 2006 (Unit gradient boundary condition)