TRANSFORMATION OF LARCH-DOMINATED FORESTS AND WOODLANDS INTO MIXED TAIGA – Permafrost simulations with HTSVS' soil model

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Motivation

A stand-alone version of the soil model of the Hydro-Thermal Soil Vegetation Scheme (HTSVS; Kramm et al. 1996, Mölders et al. 2003) is to be loosely coupled with FAREAST (e.g. Xiadong and Shugart 2005) to include the evolution of active layer depth in simulating ecosystem dynamics for a transformation of a larch- and woodland dominated landscape into taiga as observed in various areas of Siberia. For this purpose the performance in simulating soil conditions under various conditions has to be examined to develop a suitable coupling strategy. Offline evaluations (Figs. 1-4, 6-9, 13-16) are performed using lysimeter data (Brandis), data from CASE97, WINTEX, NOPEX, ATLAS and Russia. Further evaluations of HTSVS' soil model include use in meteorological models (Fig. 5), assessment by a more advanced numerical scheme (Figs. 11-12) (Galerkin weak finite elements), and theoretical analysis of uncertainty (Fig. 10) due to soil parameters. The figures shown display typical (not the best, not the worst) results.

Main features of HTSVS' soil model

- Inclusion of Dufour and Ludwig-Soret effects
- Inclusion of water vapor fluxes in the soil
- Treatment of soil freezing and thawing
- Three water phases in the soil (important for fire studies, emission of trace gases, etc.)

$$C\frac{\partial T_S}{\partial t}=\frac{\partial}{\partial z_S}\left(\lambda\frac{\partial T_S}{\partial z_S}\right)+\frac{\partial}{\partial z_S}\left(L_v\rho_w D_{T,v}\frac{\partial T_S}{\partial z_S}\right)+\frac{\partial}{\partial z_S}\left(L_v\rho_w D_{\eta,v}\frac{\partial \eta}{\partial z_S}\right)+L_f\rho_{ice}\frac{\partial \eta_{ice}}{\partial t}$$

$$\frac{\partial \eta}{\partial t}=\frac{\partial}{\partial z_S}\left(D_{\eta,v}\frac{\partial \eta}{\partial z_S}\right)+\frac{\partial}{\partial z_S}\left(D_{\eta,w}\frac{\partial \eta}{\partial z_S}\right)+\frac{\partial}{\partial z_S}\left(D_{T,v}\frac{\partial T_S}{\partial z_S}\right)+\frac{\partial K_w}{\partial z_S}-\frac{\chi}{\rho_w}-\frac{\rho_{ice}}{\rho_w}\frac{\partial \eta_{ice}}{\partial t}$$

$$C=(1-\eta_s)\rho_S c_S+\eta\rho_w c_w+\eta_{ice}\rho_{ice}c_{ice}+(\eta_s-\eta-\eta_{ice})\rho_a c_p$$

$$\lambda=\lambda_s^{(1-\eta_s)}\lambda_w^{\eta}\lambda_{ice}^{\eta_{ice}}\lambda_a^{(\eta_s-\eta-\eta_{ice})}$$

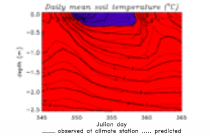


Fig. 1. Daily averaged soil temperatures at Brandis, Germany from 11 to 31 Dec 1997 as simulated and observed. Blue area: observed soil frost. Results shown after 2030d of simulation. Prior soil frost events cause the differences between the simulation without and with soil frost.

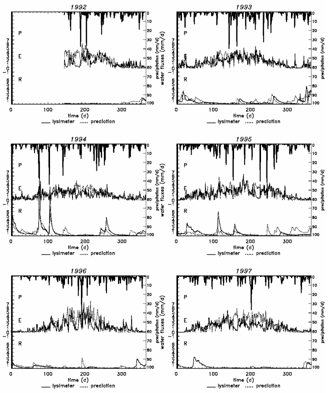


Fig. 2. Observed precipitation, P and simulated and observed daily groundwater recharge, R at 2.95m depth and water supply to the atmosphere, E for a lysimeter at Brandis from May 1992 to Dec 1997 (upper left to lower right).

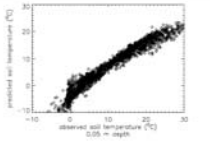


Fig. 3. Observed and simulated daily averages of soil temperature at 0.05 m depth at Brandis for May 23, 1992 to Dec 31, 1997.

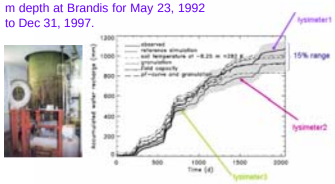


Fig. 4. Accumulated recharge. The threelysimeters contain soil with original natural soil-profile of same site. Simulations used soil-parameters derived by different methods and different lower boundary conditions.

Main results

- HTSVS' soil model captures the observed seasonal course of soil temperature well and moisture acceptably
- 20 layers and a depth of 30m provide better results than 30 layers and a depth of 30m or than 20 layers and a depth of 20m
- Assuming an annual course of soil temperature at the lower boundary in 2 or 3m depth provides typically larger discrepancies between simulated and observed soil temperatures than the simulation with 30m depth and a constant soil temperature of -9.5°C at the bottom of the soil model
- Simulated soil temperature and moisture conditions are sensitive to the assumptions made on the soil profile below the depth to which information is available
- Soil temperatures will be predicted more accurately if frozen soil physics are considered
- There is a slight sensitivity to the assumption on the initial partitioning of total soil water between the solid and liquid phase as well as the assumption on the total soil water content
- HTSVS' soil model well performs in coupled modeling setting (MM5, GESIMA)
- The largest uncertainty in simulated soil temperature caused by uncertainty in soil parameters occurs around freezing
- Using a theoretically more advanced, but computationally (1.8-2.6 times) more expensive numerical scheme improves capturing the phase of soil temperature and removes the occasional up to 10d offset in onset of thawing

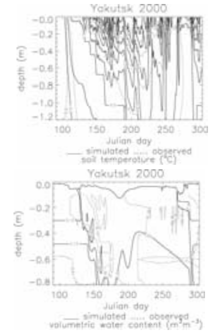


Fig. 6. Simulated and observed soil conditions at Yakutsk, Russia. Apr 1 to Oct 30, 2000. The soil model was driven with observed surface soil temperature and moisture. Time step of 1min. Below 0.97m depth a typical glacial soil profile is assumed.

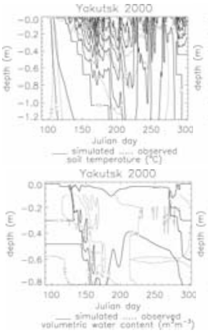


Fig. 7. Like Fig. 6, but with a 3 min time step.

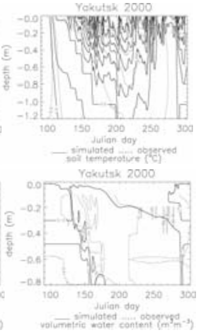


Fig. 8. Like Fig. 6 with a 1 min time step, but assuming the same soil-type as at 0.97m for entire column to 30m depth.

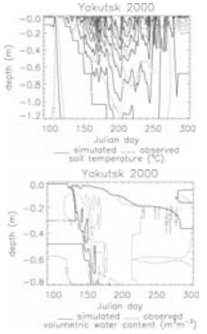


Fig. 9. Like Fig. 8, but with a time step of 5 min. Note that for larger time steps the active layer will not be captured anymore.

Table 1. Soils with on average high (H) and low (L) uncertainty for soil temperature T_s, volumetric water content η, soil-heat flux H_s, soil-moisture flux W_s, thermal conductivity λ, and hydraulic conductivity at saturation $K_{s,w}$. Uncertainty is judged with respect to the absolute uncertainty for other soils.

Soil-type	T_s	η	H_s	W_s	λ	$K_{s,w}$
sand	L		L			L
Loamy sand		L	L	L		
Sandy loam		L	L			
Silt loam					L	
loam						
Sandy clay l.					L	
Silty clay l.					L	H
Clay loam			H		L	H
Sandy clay	L	L	H	H	L	H
Silty clay			H		L	H
Clay		L	H	H	L	H
Peat	H	H	H	L	H	
Moss		H	H	L	L	
Lichen		H	H	L	L	L

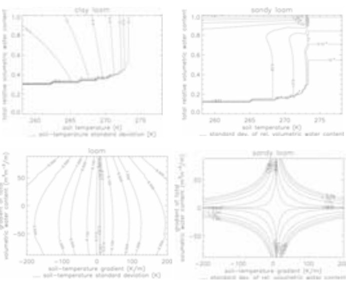
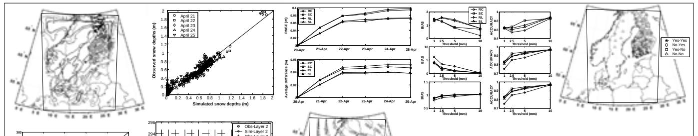


Fig. 10 Soil temperature and moisture uncertainty in dependence of soil temperature and volumetric water content (upper part) and soil moisture and temperature gradient (lower part).

Table 2. Soil parameters causing high uncertainty in predicted T_s, η, W_s and H_s. Uncertainty in density and specific heat capacity of dry soil material contribute negligibly, saturated hydraulic conductivity contributes less than pore-size distribution index b, porosity η_s, or saturated water potential ψ_s. Brackets denote impact only under certain conditions.

Soil-type	η_s	b	ψ_s
sand	η,(W_s),H_s	T_s, (W_s)	
Loamy sand		T_s, (W_s)	(T_s)
Sandy loam	W_s	T_s,η,(W_s),H_s	
Silt loam	W_s	T_s,η,(W_s),H_s	
loam		T_s,η,(W_s),H_s	
Sandy clay l.	W_s	T_s,η,(W_s),H_s	
Silty clay l.		T_s,η,(W_s),H_s	
Clay loam	W_s	T_s,η,(W_s),H_s	
Sandy clay	W_s	T_s,η,(W_s),H_s	
Silty clay		T_s,η,(W_s),H_s	
Clay		T_s,η,(W_s),H_s	
Peat	W_s	W_s	
Moss		η,(W_s)	W_s
Lichen		(W_s)	η



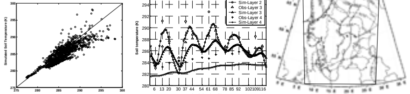


Fig. 5. Evaluation of HTSVS' soil model performance when run coupled to MM5 by use of data from the BALTEX Data Center and NCEP reanalysis data. The episode simulated is typical for snowmelt in the northern Baltic basin.

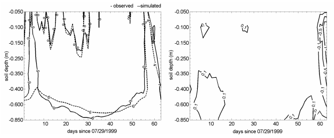


Fig 11. Simulated and observed soil temperatures for Council 1999 as obtained with the Crank-Nicholson finite difference scheme (CNFD) and Galerkin weak finite element scheme (GWFE) and differences CNFD-GWFE.

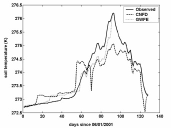


Fig. 12. Simulated and observed soil temperatures at a warm permafrost site near Council in tundra. Thawing starts on day 53.

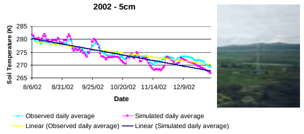


Fig. 13 Offline evaluation of daily mean soil temperature for Blueberry Hill (ATLAS data). Results for 1999, 2000, 2001 show similar agreement. Performance at deeper levels is better than at level shown.

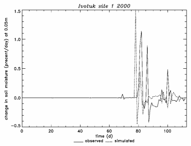
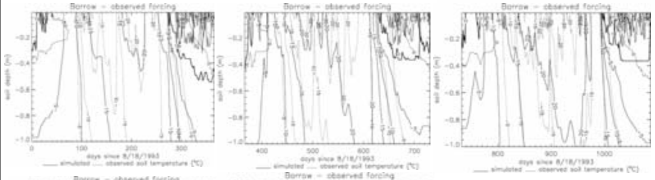


Fig. 14. Simulated and observed change in relative soil moisture at Ivotuk, AK for 3-23 to 7-13, 2000. Snow exists until 6-9.



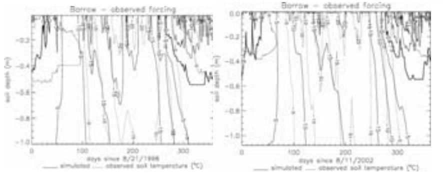
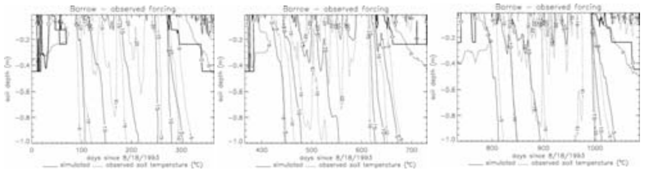


Fig. 15. Soil temperatures as obtained by a simulation without vertical distinction of soil type as typically used in atmospheric models and observed at Barrow, AK.



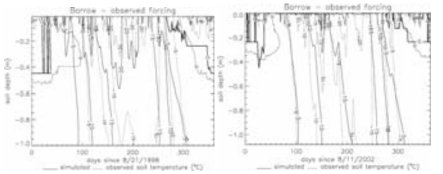


Fig. 16. Soil temperatures as obtained by a simulation with 10 layers and a lower boundary of the soil model at 2m depth as often used in weather prediction models and observed for Barrow, AK.

Acknowledgements

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