Parameterizations of organic-covered permafrost soils in land surface and hydrological models

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INTRODUCTION

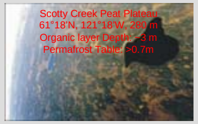
Close to one-third of the earth's surface is underlain with permafrost and much of the permafrost terrain is covered with a surface organic layer of various depths. The need to improve mathematical representation and parameterization of cold region processes in land surface and hydrological models have been well recognized in recent decades. However, progress has been hindered by (a) the complexity and variability of the soil system associated with thawing/freezing processes and organic cover and (b) the shortage of high quality field data due to the technical and logistic difficulties imposed by the harsh environments. Large variations exist in the parameterizations of thermal and hydrological processes in current land surface and hydrological models. Many of them were developed and validated in soil and climate conditions different from those in permafrost regions. In this study, efforts have been made to examine the most important thermal and hydraulic parameterizations and their effects on the simulations of ground thawing/freezing and infiltration/runoff processes against detailed measurements obtained at six field sites in Canada's discontinuous permafrost region. The tested algorithms and parameterisations include:

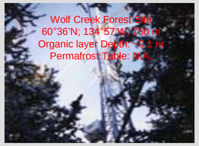
- **Five thawing/freezing algorithms**
- **Five infiltration algorithms**
- **Three soil thermal conductivity parameterisations**
- **Three soil hydraulic property parameterisations**
- **Three unfrozen water parameterisations**
- **Three parameterisations of ice impedance to hydraulic conductivity**

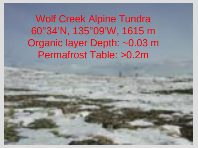
TESTED ALGORITHMS AND PARAMETERISATIONS

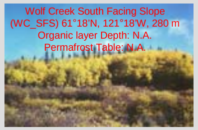
Categories	Algorithms / Parameterisations	Abbreviations	Key References
Thawing and Freezing Algorithms	Accumulated Thermal Index Algorithm	ATIA	Nelson and Outcalt, 1987; Hinkel and Nicholas, 1995
	Two Directional Stefan Algorithm	TDSA	Woo et al., 2004; Yi, et al. 2006
	Hayashi's Modified Stefan Algorithm	HMSA	Hayashi et al., 2007
	Finite difference numerical scheme with the Decoupled Energy Conservation Parameterization	FD-DECP	Verseghy, 1991; Foley et al., 1996; Shoop and Bigl, 1997;Dai et al., 2003
	Finite difference numerical scheme with the Apparent Heat Capacity Parameterization	FD-AHCP	Goodrich, 1978; Smirnova et al., 2000; Nicolsky et al., 2007
Infiltration Algorithms	Modified Green and Ampt algorithm for non-uniform soils	GA-SHAW	Flerchinger et al., 1988; Flerchinger and Saxton. 1989
	Modified Mein and Larson algorithm for non-uniform soils	ML-CLASS	Mein and Larson, 1973; Verseghy, 1991
	Instantaneous infiltration algorithm in Topoflow	IT-TOPO	Zhang et al., 2000; Peckham et al., 2009
	Gray's empirical infiltration algorithm	GRAY-IN	Gray et al., 1985; Pomeroy et al., 2007
	Zhao and Gray's parametric infiltration algorithm	ZHAO-IN	Zhao and Gray, 1997; Pomeroy et al., 2007
Soil thermal conductivity parameterisations	Complete set of Johansen's formulations	Complete-Johansen	Farouki, 1986
	Commonly used set of Johansen's formulations	Common-Johansen	Verseghy 1991; Dai et al., 2003; Woo et al., 2004; Yi et al., 2006
	De Vries's formulations	De Vries	Farouki, 1986; Flerchinger and Saxton. 1989
Soil hydraulic parameterisations	Clapp and Hornberger equations	CH-PARA	Clapp and Hornberger, 1978
	Brooks and Corey equations	BC-PARA	Brooks and Corey, 1964
	van Genuchten equations	VG-PARA	van Genuchten, 1980
Unfrozen water content parameterisations	A power function	UFW-PF	Anderson and Tice, 1972
	A segmented linear function	UFW-SL	Goodrich, 1978
	A water potential-freezing point depression function	UFW-WP	Cary and Mayland, 1972; Zhao and Gray, 1997
Ice impedance factors	Exponential ice content function	EP-Ice	Zhao and Gray, 1997
	Squared ice content function	SQ-Ice	Soulis and Seglenieks, 2008
	Linear ice content functions	LN-Ice	Bloomsburg and Wang, 1969; Flerchinger and Saxton, 1989
Inputs sources	All inputs and boundary forcing were from observation	Run1	
	Upper boundary and soil moisture were from observation; Bottom boundary was prescribed	Run2	
	Upper boundary were from observation; Bottom boundary and soil moisture were prescribed	Run3	

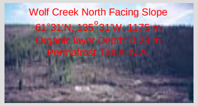
MODEL TESTING SITES











RESULTS

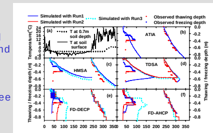


Figure 1: Observed ground thawing and freezing depths at Scotty Creek and simulations by five algorithms and three sets of model run

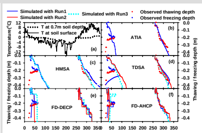


Figure 2: Observed ground thawing and freezing depths at Granger Creek and simulations by five algorithms and three sets of model run

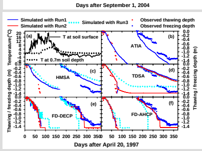


Figure 3: Observed ground thawing and freezing depths at Wolf Creek north facing slope and simulations by five algorithms and three sets of model run

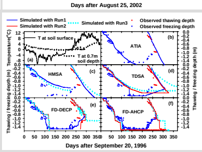


Figure 4: Observed ground thawing and freezing depths at Wolf Creek south facing slope and simulations by five algorithms and three sets of model run

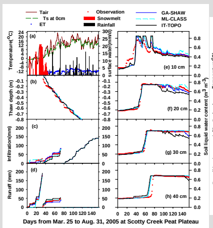


Figure 5: Observed ground thawing, infiltration, runoff and soil water content at Scotty Creek and simulations by three infiltration algorithms

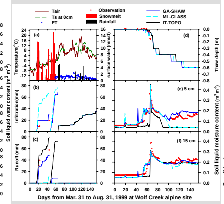


Figure 6: Observed ground thawing, infiltration, runoff and soil water content at Wolf Creek alpine site and simulations by three infiltration algorithms

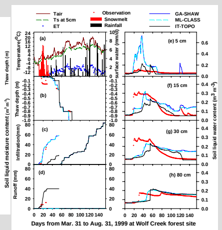


Figure 7: Observed ground thawing, infiltration, runoff and soil water content at Wolf Creek forest site and simulations by three infiltration algorithms

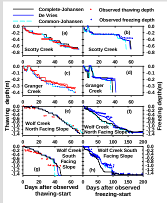


Figure 8: Observed ground thawing and freezing depths and simulations with three soil thermal conductivity parameterizations.

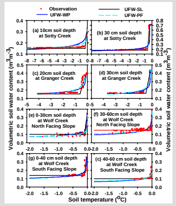


Figure 9: Observed unfrozen water content and simulations using three unfrozen water parameterizations.

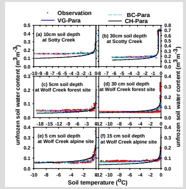


Figure 10: Observed unfrozen water content and simulations using water potential-soil temperature relationship coupled with three water retention parameterizations

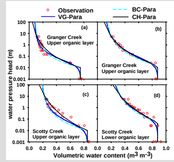


Figure 11: Soil water retention data measured at several organic soils and best fitting curves with three common parameterisations

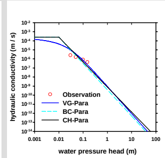


Figure 12: Observed average unsaturated hydraulic conductivity of 16 soil samples from Wolf Creek and fitting curves with three common parameterisations

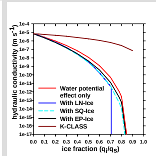


Figure 13: Reductions to hydraulic conductivity by several ice impedance parameterisations

CONCLUSIONS

- **All the empirical and semi-empirical algorithms to quantify ground thawing depth and water infiltration are subject to site specific parameter calibration, thus are not suitable for land surface and regional hydrological models that normally operate across various site conditions**
- **Numerical models with an apparent heat capacity treatment gives the most accurate simulation of ground thawing/freezing depths in permafrost sites as long as appropriate time and spatial resolutions are configurated and accurate ground surface temperature is supplied.**
- **Both analytical algorithms modified for non-uniform soil from Green-Ampt and Mein-Larson methods could simulate the infiltration into organic covered frozen and unfrozen soils reasonably well as long as soil thermal and hydraulic properties are appropriately parameterised and soil thawing depth is accurately represented.**
- **De Vries' parameterisation is recommended as the best method to parameterize the thermal conductivity in permafrost soils.**
- **The segmented linear function (UFW-SL) for unfrozen water content is the easiest to be parameterised with minimum observation data, while water potential–freezing point depression relation (UFW-WP) is the best choice for coupled numerical simulation of soil thermal and moisture transfers.**
- **With carefully chosen parameters, all three evaluated soil hydraulic parameterisations could achieve similar soil water retention curves and conductivity curves. However, van Genuchten's method gives smooth and continuous curves over all soil moisture ranges, while Brooks-Corey and Clapp-Hornberger's methods have to be capped by maximum and minimum values on saturate, extremely dry or frozen soil conditions.**
- **The lowered water potential imposed by soil freezing alone could reduce the frozen soil hydraulic conductivity to the order of magnitude of observation, the various employed ice impedance factors may not be necessary for frozen organic soils.**
- **Paired observation values of unfrozen soil water content and soil temperature could be an effective data set to derive soil hydraulic parameters of permafrost soils.**

REFERENCES

Details of all the references listed in the lower left table could be found in the following two publications:

Zhang Y., S.K. Carey, W. L. Quinton, 2008. Evaluation of the algorithms and parameterizations for ground thawing and freezing simulation in permafrost regions. Journal of Geophysical Research, 113, D17116, doi:10.1029/2007JD009343: 1761-1775.

Zhang Y., S.K. Carey, W. L. Quinton, J. R. Janowicz and G. N. Flerchinger, 2009. Simulation of infiltration into organic-covered permafrost soils (to be submitted)

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