Evaluation of the simulation algorithms and parameterization methods for ground thawing and freezing in permafrost regions

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INTRODUCTION

Ground thawing and freezing depths (GTFD) have a strong influence on the land surface hydrology and energy balances, particularly in permafrost regions. Existing algorithms to simulate GTFD have wide variations in the: (1) primary algorithms, (2) parameterisations of soil thermal properties for both frozen and unfrozen mineral and organic soils, (3) parameterisation of unfrozen water content in frozen mineral and organic soils, (4) treatment of latent energy during thawing and freezing, and (5) settings of model configurations such as resolutions of time and soil layers, and the boundary conditions. To provide guidelines for the implementation of appropriate GTFD algorithms in land surface and hydrological models, model evaluations against detailed measurements at four field sites in Canada's discontinuous permafrost regions were conducted. The evaluations include:

- Six primary algorithms including one semi-empirical, two analytical, and three numerical.
- Three soil thermal conductivity parameterisation methods.
- Three unfrozen water parameterisation methods.
- Five time resolutions ranged from 15 minutes to 1 day.
- Five resolutions of soil layers ranged from 3-layer to 15-layer.
- Six soil column depths ranged from 1 m to 10 m.
- Three sets of model runs with inputs ranged from minim prescription to maximum prescription.

TESTED ALGORITHMS, PARAMETERISATION / CONFIGRATION METHODS

Tested Primary Algorithms

- **Semi-empirical** → Accumulated Temperature Index Algorithm (ATIA)
- **Analytical** → Two Directional Stefan Algorithm (TDSA); Hayashi's Modification to Stefan Algorithm (HMSA)
- **Numerical** → Finite Difference Thermal Conduction Method with DECP (FD_DECP); Finite Difference Thermal Conduction Method with AHCP (FD_AHCP); Finite Element Thermal Conduction Method with AHCP (TONE)

$$[1]\ Z = \beta F^{0.5}$$

$$[2]\ Z = [2KF/(\rho L\theta)]^{0.5}$$

$$[3]\ Z = [2/(\rho L\theta)]^{0.5}[86400\sum(KT_s)]^{0.5}$$

$$[4]\ C\frac{\partial T(z,t)}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial T(z,t)}{\partial z}\right) + I_{lat} + I_{cov}$$

Latent Heat (I_{lat}) Parameterisation Methods

DECP: Decoupled Energy Conservation Parameterisation

AHCP: Apparent Heat Capacity Parameterisation

$$[5]\ K = \begin{cases} K_{dry}(K_{sat}/K_{dry})^{K_e} & \text{forzen peat} \quad (5a) \\ (K_{sat}-K_{dry})K_e + K_{dry} & \text{all other soils} \quad (5b) \end{cases}$$

$$[6]\ K_e = \begin{cases} \theta/\theta_0 & \text{any frozen soil} \quad (6a) \\ (\theta/\theta_0)^2 & \text{unfrozen peat} \quad (6b) \\ 0.7\log(\theta/\theta_0)+1.0 & \text{unfrozen coarse minreal soil} \quad (6c) \\ \log(\theta/\theta_0)+1.0 & \text{unfrozen fine mineral soil} \quad (6d) \end{cases}$$

$$[7]\ K_{dry} = \begin{cases} 0.05 & \text{unfrozen peat} \quad (7a) \\ 0.55 & \text{frozen peat} \quad (7b) \\ \frac{0.135\rho_b+64.7}{2700-0.947\rho_b} & \text{natural minreal soil} \quad (7c) \\ 0.039\theta_0^{-2.2} & \text{crushed rock} \quad (7d) \end{cases}$$

$$[8]\ K_{sat} = \prod_{i=1}^{N}(K_i)^{\theta_i}$$

$$[9]\ K = \frac{\theta_w K_w + f_a\theta_a K_a + f_s\theta_s K_s}{\theta_w + f_a\theta_a + f_s\theta_s}$$

$$[10]\ f_s = \frac{1}{3}\left[\frac{2}{1+(K_s/K_w-1)0.125} + \frac{1}{1+(K_s/K_w-1)0.75}\right]$$

$$[11]\ f_a = \frac{1}{3}\left[\frac{2}{1+(K_a/K_w-1)g_a} + \frac{1}{1+(K_a/K_w-1)g_c}\right]$$

$$[12]\ g_a = \begin{cases} 0.333 - \frac{\theta_a}{\theta_0}(0.333-0.035) & \theta_w > 0.09 \\ 0.013 + 0.944\,\theta_w & \theta_w \le 0.09 \end{cases}$$

$$[13]\ g_c = 1 - 2g_a$$

$$[14]\ \theta_u = a|T|^c$$

$$[15]\ \theta_u = \theta_0\left(\frac{\psi}{\psi_0}\right)^{-1/b} = \theta_0\left[\frac{L(T_k - T_{k,f})}{gT_k\psi_0}\right]^{-1/b}$$

$$[16]\ \theta_u = \begin{cases} \theta_w - \frac{T_f - T}{T_f - T_{u,l}}(\theta_w - \theta_{u,l}) & T > T_{u,l} \\ \theta_{u,l} & T \le T_{u,l} \end{cases}$$

Table 1: Tested soil parameterisation and model configuration methods

Tested Items	Tested methods / schemes	Applicable Algorithms
Soil thermal conductivity	A complete Johansen's formulation (Eqs. 5-8); A commonly used Johansen's formulation (Eqs. 5b, 6a, 7c and 8); a simplified de Vries's formulation (Eqs. 9-13)	All but ATIA
Unfrozen water content	A power function (Eq. 14); A water potential-freezing point depression function (Eq. 15); A segmented linear function (Eq. 16)	FD_DECP, FD_AHCP, TONE
Time resolution	15 minutes; 30 minutes; 60 minutes; 0.5 day; 1 day	FD_DECP, FD_AHCP, TONE
Resolution of soil layers	3 layers; 6 layers; 9 layers; 12 layers; 15 layers	All but ATIA
Soil column depth	1 m; 2 m; 3 m; 4 m; 5 m; 10 m	FD_DECP, FD_AHCP, TONE
Inputs sources	Run1: all inputs were from observation; Run2: Observed top boundary and soil moisture, prescribed bottom boundary; Run3: Observed top boundary and prescribed bottom boundary and soil moisture	All. Run1, Run2 and Run3 are same for ATIA, and Run1 and Run2 are same for HMSA

Model Testing Sites

Table 2: Site conditions

Site	Geographic Coordinates	Vegetation	Organic Layer Depth	Permafrost Table
SC	61 º 18'N; 121º18'W, 280 m	Spruce forest	3.0 m	> 0.7 m
GC	60 º 33'N; 135º11'W, 1338 m	Willow shrub	0.35 m	> 0.4 m
WC_NFS	60 º 31'N; 135º31'W, 1175 m	Black-spruce forest	0.23 m	> 1.4 m
WC_SFS	60 º 31'N; 135º31'W, 1175 m	Aspen forest	No	No

RESULTS

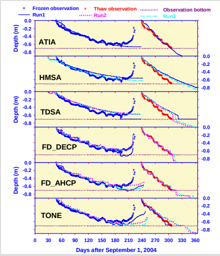

Figure 3: Tests of six thaw/freeze algorithms at Scotty Creek

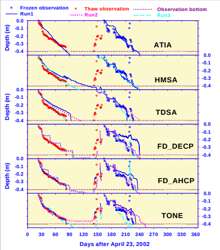

Figure 4: Tests of six thaw/freeze algorithms at Granger Creek

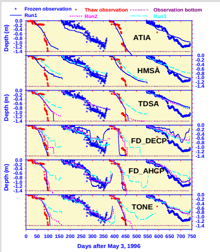

Figure 5: Tests of six thaw/freeze algorithms at Wolf Creek North Facing Slope

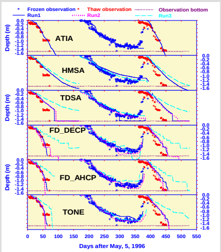

Figure 6: Tests of six thaw/freeze algorithms at Wolf Creek South Facing Slope

Table 3: RMSDs [(1)] between a run with 15 minute time resolution and runs with coarser time resolutions

Processes	Soil layers	FD_DECP	FD_AHCP	TONE
Thawing depth (m)	30 minutes	0.010	0.002	0.002
	60 minutes	0.022	0.021	0.048
	0.5 day	Run failed	Run failed	0.051
	1 day	Run failed	Run failed	0.055
Freezing depth (m)	30 minutes	0.014	0.006	0.001
	60 minutes	0.020	0.008	0.002
	0.5 day	Run failed	Run failed	0.012
	1 day	Run failed	Run failed	0.023

Note [(1)] RMSD: Root mean squared differences

Table 4: RMSDs between a run with 15 soil layers and runs with coarser soil layer settings

Processes	Soil Layers	HMSA	TDSA	FD_DECP	FD_AHCP	TONE
Thawing depth (m)	3 layers	0.043	0.084	2.747	1.570	0.238
	6 layers	0.036	0.056	0.210	0.218	0.142
	9 layers	0.021	0.002	0.113	0.115	0.069
	12 layers	0.007	0.0	0.077	0.048	0.055
Freezing depth (m)	3 layers	0.062	0.368	0.811	1.27	2.150
	6 layers	0.046	0.004	0.085	0.090	0.071
	9 layers	0.031	0.003	0.071	0.076	0.056
	12 layers	0.005	0.0	0.045	0.047	0.034

Table 5: RMSDs between a run with 10 m soil column depth and runs with shallower soil column settings

Processes	Soil column depth	SC	GC	WC_NFS	WC_SFS
Thawing depth (m)	1.0 m	0.057	0.030	1.591	0.158
	2.0 m	0.019	0.016	0.884	0.078
	3.0 m	0.011	0.011	0.187	0.013
	4.0 m	0.008	0.005	0.071	0.012
	5.0 m	0.005	0.005	0.031	0.011
Freezing depth (m)	1.0 m	0.008	0.049	0.216	0.226
	2.0 m	0.002	0.038	0.049	0.120
	3.0 m	0.0	0.029	0.057	0.062
	4.0 m	0.0	0.022	0.003	0.060
	5.0 m	0.0	0.016	0.002	0.030

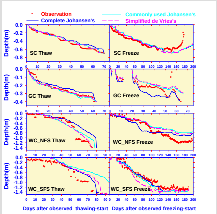

Figure 1: Tests of soil thermal conductivity parameterisation with TONE

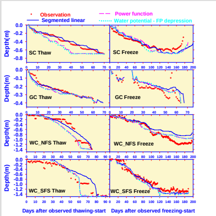

Figure 2: Tests of unfrozen soil water parameterisation with TONE

CONCLUSIONS

- A simplified de Vries's formulation (Eqs. 9-13) generated reasonable GTFD simulations at all the four tested sites, while a commonly used Johansen's formulation (Eqs. 5b, 6a, 7c and 8) only achieved good results at the three organic covered permafrost sites. The formulations designed for peat (Eqs. 5a, 6b, 7a and 7b) did not improve the GTFD simulations at the organic soils of the tested sites (SC, GC and WC_NFS), while the formulations for frozen and unfrozen soils (6a and 6c) greatly improved the GTFD simulations at the mineral soil site (WC_SFS).
- All the three unfrozen water parameterisation methods (Eqs 14 - 16) achieved reasonable GTFD simulations when appropriate coefficients were chosen. However, the parameters in the segmented linear function (Eq. 16) are easier to estimate than the coefficients in the other two methods.
- The analytical algorithms are less sensitive to resolution of soil layers than the numerical models. A six-layer resolution worked well for both HMSA and TDSA, while at least nine soil layers were needed in the 5-m soil column for the three numerical models, in order to simulate the GTFD with acceptable accuracy.
- Numerical models normally require sub-hourly time resolutions. TONE, with a finite element scheme, was the only numerical algorithm that worked at half a day and daily time resolution during the model tests.
- The appropriate position of soil lower boundary for the numerical algorithms is largely related to the site condition and the simulation time scale. For runs within a decade scale as tested in this study, 1 m depth was enough for SC and GC sites, where the active layer depths were within 0.7 m, and at least 4 m depth was required for WC_NFS and WC_SFS, where the active layer or seasonal frost depth were approximately 1.4-1.5 m.
- The semi-empirical algorithm ATIA worked well at all the four tested sites when site-calibrated coefficients (β) were used. However, due to the large variations of the β values from thawing to freezing, from site to site and from year to year, it is not recommended to apply this method to dynamic analyses of GTFD.
- The two analytical algorithms HMSA and TDSA performed similarly at almost all sites. Performance was improved at wetter sites (SC and GC) than at drier sites (WC_NFS and WC_SFS).
- All three numerical algorithms (FD_DECP, FD_AHCP and TONE) traced GTFD evolutions more precisely than other algorithms at all sites, particularly when observed and best estimated soil moisture was supplied (Run1 and Run2). Among the three, FD_AHCP and TONE performed similarly and better than FD_DECP at certain sites (e.g. WC_NFS and GC).
- Assuming a zero heat flux at 5 m depth (Run2) in the three numerical algorithms generated comparable results than using the observed bottom boundary temperature (Run1) at all 4 sites. Assuming soil saturation (Run3) worked well at GC and SC sites, but caused large errors at WC_NFS and WC_SFS sites.

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