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Interactive comment on "Modeling the impact of wintertime rain events on the thermal regime of permafrost" *by* S. Westermann et al.

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The manuscript provides modeling results of the effects of rain on snow on the thermal regime of a permafrost soil in a maritime arctic climate.
As far as the overall structure, the manuscript is well written and allows the reader to understand the research questions behind the problem. Furthermore, the results are deeply commented and discussed.
As far as the modeling scheme is concerned, two major comments are reported:

1. the modeling scheme is not accurately documented, which makes it difficult to be reproduced. Further details on the equations should be provided in the Appendix;
2. the paper does not cite the latest "cold-hydrology" models present in literature, e.g. SHAW (Flerchinger, 1991), COUP (Staehli et al., 1996) and GEOtop (Rigon

et al., 2006; Endrizzi et al., 2011) that study the effects of coupled heat and water transfer in permafrost.

The paper may be published if the authors provide a more exhaustive explanation of the modeling equations and details (see Section "Comments on the equations"). Below I have listed a number of other comments that should be addressed prior to publication.

Comments on the text

- pg. 1702 line 6: $K(z,T)$ and c_{eff}: add measurement unit;
- pg. 1702 line 12: θ_α and c_α: add measurement unit;
- pg. 1702 Eq. (1): provide reference;
- pg. 1702 line 6: "effective heat capacity": provide reference;
- pg. 1703 lines 1-4: it is not clear if $\theta_w^{max} = \theta_s$ or $\theta_w^{max} < \theta_s$ where θ_s is the soil porosity. Furthermore, I would like to now whether in the simulation the soil is considered always saturated or unsaturated;
- pg. 1704 line 5: $\theta_0 = 0.1$: in Table 2 one realizes that $\theta_0 = 0.0$: please explain;
- pg. 1704 line 6: ϵ_s: add measurement unit;
- pg. 1705 Eq. (10): provide reference;
- pg. 1705 lines 11 and 12: "... so that a snow density of 350 kg m^{-3} corresponds to a volumetric ice content of $\theta_i = 0.35$".
  The density of snow ρ_{sn} (kg m^{-3}) results:

$$\rho_{sn} := \frac{M_{sn}}{V_{sn}} \quad (1)$$

where M_{sn} (kg) is the mass of the snow contained in the snow volume V_{sn} (m^3). The snow is composed by water ($_w$) and ice ($_i$) particles so, as the mass and volumes are additive quantities, the mass and volume of snow become:

$$M_{sn} = M_w + M_i \qquad (2)$$
$$V_{sn} = V_w + V_i$$

One can define the volumetric water θ_w (-) and ice content θ_i (-) as respectively $\theta_w = V_w/V_{sn}$ and $\theta_i := V_i/V_{sn}$. The snow density eventually becomes:

$$\rho_{sn} = \rho_w\theta_w + \rho_i\theta_i \qquad (3)$$

from which θ_i becomes:

$$\theta_i = \frac{\rho_{sn}}{\rho_w} - \theta_w \qquad (4)$$

Now, if the snow density is 350 kg m^{-3}, the ice content results:

$$\theta_i = 0.35 - \theta_w \qquad (5)$$

According to this notation, $\theta_i = 0.35$ only if $\theta_w = 0$.
Please explain.

- pg. 1705 lines 17-21: I imagine you mean that, according to the measurements of heat diffusivities, $K_{fresh} = 0.3$ W m K^{-1} and $K_{old} = 0.55$ W m K^{-1}. However, in Table 3 one reads: $K_{fresh} = 0.2$ W m K^{-1} and $K_{old} = 0.7$ W m K^{-1} for the snow. Furthermore, you say that the thermal diffusivities are measured at the bottom of the snow pack but in Table 3 the bottom ice layer is characterized by higher values. Please explain better the context.

- pg. 1705 line 23: add measurement unit for P;

- pg. 1706 lines 14-15: "... the thermal properties of the snow remain unchanged during and after an infiltration event". Please add measures or literature references that confirm this sentence.

- pg. 1706 line 22: In order to distinguish between rain, slush and snow, I would plot also the air temperature, if present, that could help in decreasing the uncertainty;

- pg. 1707 line 18: σ_s and ϵ_s: add measurement unit;

- pg. 1707 line 28 and pg. 1798 line 1: the initial condition at 10 m is set to -3.9°C equal to the temperature at 1.52 m and then you considered a temperature of 0°C at 100 m depth.

  * please specify if from 1.52 to 10 m you considered a uniform profile equal to -3.9°C;
  * please specify the reason for this assumption: the initial condition at depth (approximately below 4 m) take a lot of spin-up time to set to equilibrium with the forcing to the system, so any arbitrary assumption on the initial condition has to be fully detailed and justified.
  * please specify if from 10 m to 100 m which profile you considered (e.g. linear) and justify it.

- pg. 1716 lines 17-19: "... the freezing would ... "". The text is confused. What does it mean that the soil is first warmed by the latent heat and then cooled by heat conduction through the snow? At pg. 1711 line 11 you say that the heat conduction is impeded by the overlying snow layers.
  Please explain.

- Table 1 pg. 1728: add column with measurement unit;

- Table 2 pg. 1729: you show the values for bedrock and soil: what porosity are you considering for soil and bedrock? In general you should specify the values used for θ_w, θ_i, θ_a, θ_m and θ_o to derive the values of C_{frozen}, C_{thawed}, K_{frozen} and K_{thawed} both for soil and bedrock.

Comments on the equations

In general, I would require a deeper explanation on the modeling hypothesis and assumptions, with clearer passages in order to ease the comprehension. This paper, indeed, is based on modeling and therefore must precisely explain the details. Below some inherent questions:

1. Equation (1) at pg. 1702 may be written as:

$$\frac{C_{sn}}{L\,\Delta t}\left(T^{n+1}-T^{n}\right)-\frac{\theta_i^{n+1}-\theta_i^{n}}{\Delta t}-\frac{\partial}{\partial z}\left(K\,\frac{\partial T}{\partial z}\right)=0 \tag{6}$$

   where the subscript $_{sn}$ stands for snow, Δt is the integration interval and the superscript ^{n} and $^{n+1}$ stand for the time discretization. Considering that:

$$\theta_i=\theta_{tot}-\theta_w \tag{7}$$

   one gets that:

$$\theta_i^{n+1}-\theta_i^{n}=\theta_{tot}^{n+1}-\theta_{tot}^{n}+\theta_w^{n}+\theta_w^{fc}-\theta_w^{n+1}-\theta_w^{fc} \tag{8}$$

   Furthermore, one realizes that:

$$T^{n+1}-T^{n}=T^{n+1}-T_f+T_f-T^{n} \tag{9}$$

   Eq. (6) after some calculations becomes:

$$\frac{C_{sn}}{L\,\Delta t}\left(T_f-T^{n}\right)+\frac{\theta_w^{fc}-\theta_w^{n}}{\Delta t}-\frac{1}{L}\cdot\frac{\partial}{\partial z}\left(K\,\frac{\partial T}{\partial z}\right)= \tag{10}$$

$$=-\frac{C_{sn}}{L\,\Delta t}\left(T_{n+1}-T_f\right)-\frac{\theta_w^{n+1}-\theta_w^{fc}}{\Delta t}-\frac{\theta_{tot}^{n}-\theta_{tot}^{n+1}}{\Delta t}$$

   The questions are:

   - how can one derive Eq. (A1) and (A2) at pg. 1720 from the above Eq. (10);
   - where do τ_1 and τ_2 come from?

2. Eq. (A3) pg. 1720: what are the measurement units? (mm s^{-1})?

3. What is the index "n" in Eq. (A5) at pg. 1721?

4. I have seen just the energy balance (see Eq. (1) for the soil and Eq. (10) for the snow). What about the mass balance? What assumption and equation are you using? I think that should be thoroughly explained. See Dall'Amico et al. (2011) for an extended description of water and energy balance equations.

References

Dall'Amico, M., S. Endrizzi, S. Gruber, and R. Rigon (2011), A robust and energy-conserving model of freezing variably-saturated soil, The Cryosphere, 5, 469–484.
Endrizzi, S., L. Quinton, and P. Marsh (2011), Modelling the spatial pattern of ground thaw in a small basin in the arctic tundra, The Cryosphere Discussion, 5, 367– 400.
Flerchinger, G. (1991), Sensitivity of soil freezing simulated by the SHAW model, Transactions of the ASAE, 34(6), 2381–2389.
Rigon, R., G. Bertoldi, and T. M. Over (2006), GEOtop: a distributed hydrological model with coupled water and energy budgets, J. Hydromet., 7, 371–388.
Staehli, M., P. Jansson, and L. Lundin (1996), Preferential water flow in a frozen soil - A two-domain model approach, Hydrological Processes, 10, 1305–1316.

Interactive comment on The Cryosphere Discuss., 5, 1697, 2011.