The Cryosphere Discuss., 4, C1781–C1790, 2011
www.the-cryosphere-discuss.net/4/C1781/2011/

The Cryosphere
Discussions

Interactive comment on "An energy-conserving model of freezing variably-saturated soil" *by* M. Dall'Amico et al.

M. Dall'Amico et al.

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Received and published: 28 March 2011

We are grateful for the thorough and constructive comments of Referee #2 that have helped to improve the strongly revised manuscript. Below, we have listed the essence of each issue raised together with a short reply and the revised text or its location where appropriate.

Comment: The suggested 'new energy-conserving model' is actually a 'new numerical scheme' for existing energy and water transfer equations.

Reply: Yes, the novelty in the numerical scheme is: (i) the description of the ice-water freezing scheme in a non saturated condition; (ii) the conservative discretization on the internal energy formulation; (iii) the globally convergent scheme to cope with the

high non-linearity; (iv) the detailed explanation of the splitting method to decouple the system of equations.

Comment: The benefits over previous schemes (e.g. Zhao et al. 1997; Hansson et al. 2004) need to be demonstrated better and testing conditions extended beyond previous work. For instance, two major limitations of coupled energy and water transfer numerical schemes in frozen soil (Zhang et al 2009) application are: (1) success in non-uniform soil; and (2) convergence and efficiency in large flux conditions such as snow melt infiltration. If the numeric scheme of this study could demonstrate its success in any of above conditions, its potential applications in cold region land surface and hydrological modeling could be enormous. Such testing data are rare, but still possible (e.g. Zhang et al, 2009).

Reply: You are right and we have added a further test with respect to infiltration into frozen soil (see new Figure 9), to highlight the improvement of the algorithm with respect to its predecessors . However, this paper deals with the numerical and mathematical approach, rather with a full application on real case study which would require exceedingly much space. The paper by Endrizzi et al (submitted) may be referred to as a proper application of this new method. That paper shows that the method works in the conditions indicated by the reviewer.

Comment: Provide evidence or tests to show it is indeed an energy-conserving numerical scheme.

Reply: He have added a plot that show the energy conserving capability of the scheme.

Changes: See new Figure 6 for the energy conserving capabilities and Figure 8 for the number of required iterations

Comment: Energy or mass balance equations or coupling methods (L. 15 P. 1245 to L. 11 P. 1254) are not new but numerical techniques (L. 12 P. 1254 to L. 28 P. 1259) differ from previous studies. This should be reflected in the title.

Reply: We have changed the title.

Changes: The new title is: A robust and energy-conserving model of freezing variably-saturated soil

Comment: P. 1247 L. 10-11: ‘to our knowledge this equation has never been fully derived from a thermodynamical point of view leaving some doubt on its limitations’. The derivation of Zhao et al., 1997 was from a thermodynamical point of view and quite similar.

Reply: Zhao et al., (1997) Eq. (12) is referred to as “the maximum liquid water content at sub-zero temperature” and is called the relation as “freezing point depression equation”. In our text, however, we call “freezing point depression” the Equation (6) (Equation (17) in the new version), which sets the temperature of phase change of an unsaturated soil. Watanabe and Mizogouchi (2002) refer this depressed temperature to the Gibbs-Thomson effect. The liquid water content at sub-zero temperature in our paper is given by Equation (9) (equation (23) in the new version) and this takes into account not only the temperature under freezing conditions (as Zhao et al, 1997) but also the depressed melting temperature that depends on the total water content (i.e. on the air entry potential). Furthermore, we consider also the total volumetric water content (ice and water fractions) in deriving the unfrozen water content formulation, differently from Zhao et al (1997) that consider that the unfrozen liquid volume is only a function of temperature, according to Jame (1972). We believe that our approach is more general and less empirical.

Comment: P. 1247, L. 22-23: ‘The energy equation with freezing soil in the above considered literature is always written in a non-conservative form’. It seems that all the energy balance equations in this study (Eq. 16), or in Zhao et al. (1997, Eq. (1)) or in Hansson et al. (2004, Eq. (7)) are similar and energy conservative. The only difference is that this study presented in a more generalized 3D form while the other two presented in a specific 1D form.

Reply: Actually it is true that we are not the only one to write the equation in a conservative form. We have done a further review (below reported) by which one realizes that, even though most of the authors write it non-conservative, others write it conservative. The difference in our notation is that we always use the conservation of internal energy rather than differentiating between sensible and latent term. This allows to obtain a more general form of the diffusion-advection equation, similar to the mass balance equation. Thus the numerical method used in the energy equation can be further used to the mass balance equation. Finally, we use a more generalized 3D form.

Changes: We removed the text “The energy equation with freezing soil in the above considered literature is always written in a non-conservative form”

CONSERVATIVE FORM Zhao et al. (1997) conservative eq. 1

Harlan (1973) conservative eq. 4

Hansson et al. (2004) conservative eq. 7

Daanen et al. (2007) conservative eq. 11

Staehli et al. (1996) conservative eq. 1

Zhao and Gray (1999) conservative

NON CONSERVATIVE FORM

Zhang et al. (2008) non conservative eq. 4

Jame and Norum (1980) non conservative eq. 1

Newman and Ward Wilson (1997) non conservative eq. 4

Guymon and Luthin (1974) non conservative eq. 12

Ling and Zhang (2004) non conservative eq. 13

Ochsner and Baker (2008) non conservative eq. 1

Smirnova et al. (2000) non conservative eq. 6

Viterbo et al. (1999) representation non conservative eq. 1

Zhang et al. (2010) comparison non conservative eq. 26

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Comment: Equation 5: I believe that Lf is missing in the two terms from right.

Reply: You are right, we have provided the corrections.

Comment: Equation 6: Needs more explanation for H () term.

Reply: You are right, the text was obscure and the mathematical passages cumbersome. We have changed and improved the text, explaining the origin of the Haeviside function.

Comment: Figure 3: Check the legends of line style for ‘An’ and ‘Sim’. They are not differentiable.

Reply: You are right, we have improved the readability of the Figure 3.

Interactive comment on The Cryosphere Discuss., 4, 1243, 2010.

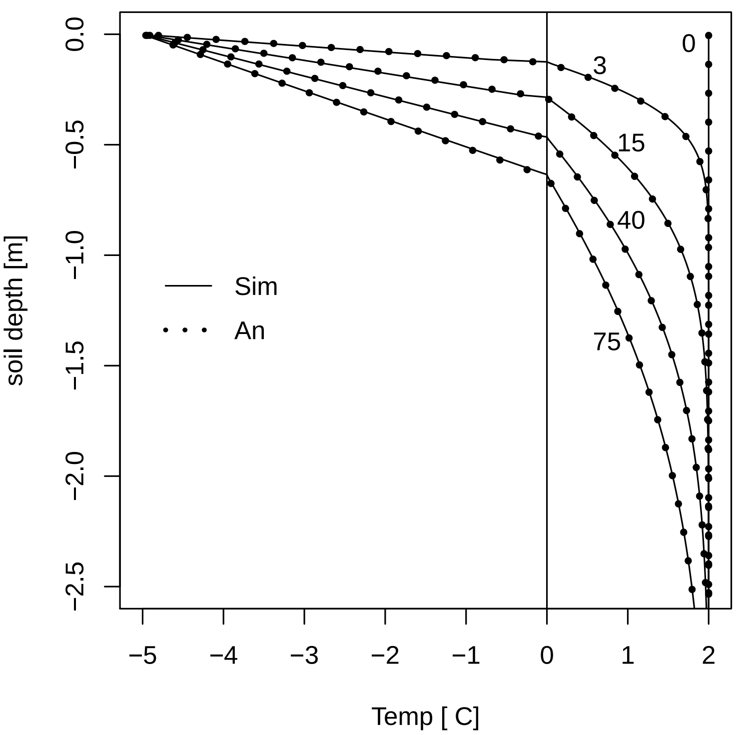

Fig. 1. enhanced b/w printing capabilities of Fig. 3 (Comparison between the simulated numerical and the an- alytical solution. Soil profile temperature at different days. Grid size=10 mm, N=500 cells)

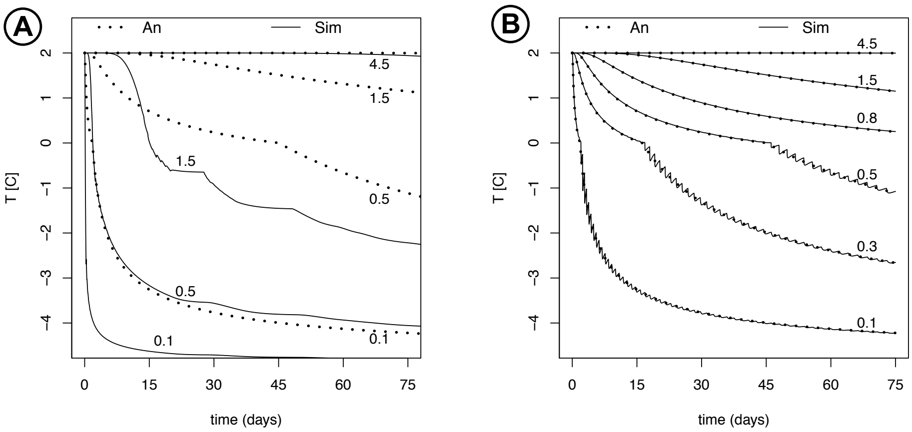

Fig. 2. enhanced b/w printing capabilities of Fig. 3 (bis). X-axis represents the time. Left: comparison against non-globally convergent Newton scheme. Right: globally convergent scheme

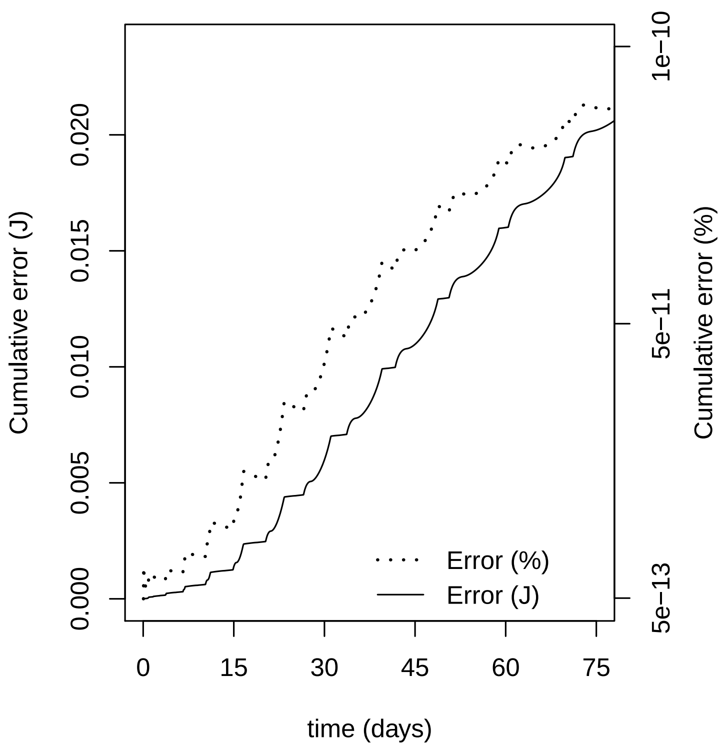

Fig. 3. Cumulative error associated with the the glob. conv. Newton scheme. Plain: cumulative error (J), dotted: cumulative error (%) as the ratio between the error and the total energy of the soil