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Interactive comment on "A Simple Temperature-Based Method to Estimate Heterogeneous Frozen Ground within a Distributed Watershed Model" *by* Michael L. Follum et al.

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We would like to thank Referee #1 for their comments and suggestions. We appreciate all their insights about the paper and hope our responses address their suggestions and facilitate further discussion.

Main Issue #1, The frozen ground index method proposed requires numerous forcing data, therefore why use it instead of an energy balance approach?: The main goal of this study is to develop a frozen ground method that can be used within a

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Discussion paper

variety of watershed models, and we believe that the new modCFGI model has two significant advantages within this context. First, many watershed models do not explicitly simulate soil moisture, which would be required to implement an energy balance method. The modCFGI method can also use soil moisture to simulate the depth of frozen ground (as presented in this study), but soil moisture is not required to simulate the presence/absence of frozen ground. Thus, the modCFGI method can still be used to identify frozen soil for runoff production purposes even when soil moisture is not simulated. Second, the modCFGI method still requires fewer types of forcing data and fewer parameters than energy balance models. For example, the attached figure compares the forcing data requirements for two energy balance models (COUP and SHAW) along with the data requirements for the pre-existing CFGI model and the new modCFGI model. The energy balance models both require radiation data that are not readily available for many watersheds. In contrast, modCFGI model requires cloud cover data, which are routinely measured at most airports (data archived in the U.S. at the National Centers for Environmental Information, https://www.ncdc.noaa.gov/) as well as many meteorological stations. Although it is difficult to determine the total number of parameters that are required by energy balance models, the modCFGI likely requires specification of many fewer parameters, which reduces the potential for equifinality. In the revised paper, we plan to include a clearer statement of the paper's goals in the Introduction section, a short discussion of data requirements in the Model Application section, and a discussion of the model's use in data-sparse environments in the Conclusions.

Main Issue #2, Results are OK, but not exciting.: We agree that simulating temporal variability of frost depth remains a difficult problem for this model and others. However, the results in this paper are still a valuable contribution for three reasons. First, although temperature index models are commonly used in practice, very few studies have tested such models against observed frost depths. This study provides a rare evaluation of the existing CFGI model. Second, the proposed modCFGI model performs much better than the CFGI model in capturing the spatial variability of frozen ground within the watershed (Figures 5 and 6). Figure 6 shows that the modCFGI model better captures the different frost depths at the various sites in the watershed. Accurate representation of the spatial pattern of frozen ground is expected to be important in capturing its role in flood production. Regarding temporal variability, the modCFGI better reproduces the high (e.g., WY 2007) and low (e.g. WY2008) frost depths and better captures the presence of frozen ground (Table 6). Third, the results suggest that litter depth is an important control on frost depth (last paragraph on page 21).

Specific Comment #1, Interesting to see comparison of radiation-derived proxy temperature (T_rad) to air temperature (T_a).: The values of T_rad tend to be higher than T_a when a cell has more direct sunlight (due to the cell's aspect and slope). Cloud and canopy cover also affect the T_rad pattern. In contrast, T_a in the CFGI model is estimated only using elevation. The impact of T_rad on snowpack was examined in Follum et al. (2015). We agree with the reviewer that a comparison between T_rad and T_a is important for the present study, and we will add this comparison to the results (likely in section 4.1) in the revised manuscript. Also, the effects of canopy that were highlighted in Webster et al. (2017) will be included in the discussion of the results.

Specific Edit Page 2, Line 17 "When the frost index exceeds a threshold, the soil is considered frozen and impermeable to infiltration.": We agree that frozen soils are not completely impermeable to infiltration, especially in forested environments (Lindstrom et al. 2002; Bayard et al., 2005; Nyberg et al., 2001; Shanley and Chalmers, 1999). However, this statement is referring to how some hydrologic models use degree-day frozen ground methods (such as CFGI) to restrict infiltration. In the revised manuscript, a clarification will be added (with citations) that indicates that this approach sometimes deviates from reality.

Specific Edit Page 20, Line 7 "...because any frozen ground has the potential to impede infiltration and produce flooding.": This statement will be modified to: "...because even shallow frost with high moisture content (concrete frost) has the potential to impede infiltration and produce flooding."

Specific Edit Page 8, Line 30 Description of frost tubes.: The CRREL-Gandahl frost tubes (Ricard et al., 1976) were used at SREW. The reviewer is correctâĂŤthe frost tubes were filled with a methylene blue solution where freezing depth is identified by a change in colour within the tube (blue indicates thawed, clear indicates frozen). More details on the method of frost depth measurement will be provided on Page 8, with a reference to Vermette and Kanack (2012) who include images and descriptions of frost tubes that are similar to those used at SREW.

Specific Edit Pages 18 and 19, Figures 5 and 6: We agree with the reviewer that the change in elevation (and thus temperature) has small effect on snow and frozen ground within SREW. We appreciate the recommendation to cite the recent work by Stähli (2017), and we will include it in the results and discussion section.

Specific Edit Pages 25-29 Cited literature almost exclusively from North America.: We agreeâĂŤresearch outside of North America will be added including numerical modelling approaches such as COUP (Jansson 2001; Jansson and Karlburg, 2010) and DWHC (Chen et al., 2007) and field investigations (Stähli 2017; Lindstrom et al. 2002; Bayard et al., 2005; Bayard and Stähli, 2005; Nyberg et al., 2001).

Specific Edit Pages 25-29 Inclusion of Campbell et al., (2010).: The research by Campbell et al. (2010) is related to our work and will be included in the Introduction and the Results and Discussion sections.

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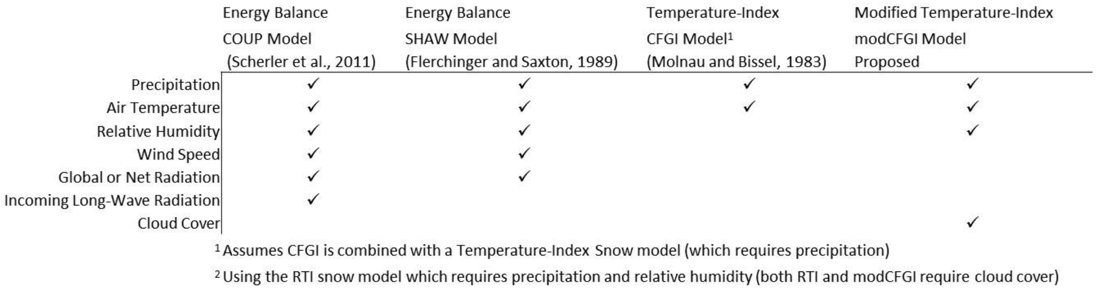

	Energy Balance COUP Model (Scherler et al., 2011)	Energy Balance SHAW Model (Flerchinger and Saxton, 1989)	Temperature-Index CFGI Model[1] (Molnau and Bissel, 1983)	Modified Temperature-Index modCFGI Model Proposed
Precipitation	✓	✓	✓	✓
Air Temperature	✓	✓	✓	✓
Relative Humidity	✓	✓		✓
Wind Speed	✓	✓		
Global or Net Radiation	✓	✓		
Incoming Long-Wave Radiation	✓			
Cloud Cover				✓

[1] Assumes CFGI is combined with a Temperature-Index Snow model (which requires precipitation)

[2] Using the RTI snow model which requires precipitation and relative humidity (both RTI and modCFGI require cloud cover)

Fig. 1. Required forcing data for the COUP, SHAW, CFGI, and modCFGI frozen ground models.