Supplementary for

Comparative Hydrological Modeling of Snow-Cover and Frozen Ground Impacts Under Topographically Complex Conditions

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1. Governing equations

The criteria for hydrological model simulation performance are defined as flows:

$$RMSE = \sqrt{\sum_{i=1}^{n} (X_s - X_o)^2 / n} \tag{S18}$$

$$BIAS = \sum_{i=1}^{n} (X_s - X_o)/n \tag{S19}$$

$$NSE = 1 - \sum_{i=1}^{n} (X_s - X_o)^2 \Big/ \sum_{i=1}^{n} (X_o - \overline{X_o})^2 \tag{S20}$$

$$RE = \left(\sum_{i=1}^{n} (X_s - X_o) \Big/ \sum_{i=1}^{n} X_o \right) \times 100\% \tag{S21}$$

where X_s represents the simulated values, X_o represents the observed values, $\overline{X_o}$ is the mean of the observed values, and n is the number of time series observations.

2. Implementation

Using the observed ground surface temperature data from six meteorological stations within the basin, the initial freezing and thawing dates of the frozen surface layer were determined and compared with the model simulation results, with missing data points from station 56158 for the period 2015-2018. As shown in Figure S5, the observed and simulated results were quite similar; the upstream stations (56034 and 56038) exhibited earlier freezing (October) and later thawing (April) compared to the four midstream stations. Additionally, all stations during the study period showed a trend of delayed onset of freezing and earlier onset of thawing. Although the number of stations is limited, the point-scale data provided strong validation for the simulated soil freeze-thaw processes.

Furthermore, the relationships between the initial freezing date, last freezing date, and the freezing days of seasonally frozen ground (Fig. S6 (a)), as well as the first snow day, last snow day, and the number of snow cover days (Fig. S6 (b)) were analyzed. The results indicate that the initial freezing date of the soil generally occurred earlier than the snow accumulation date, and the last thawing day was later than the last snow day. This implies that the number of freezing days of the soil exceeds the number of snow cover days. According to the simulation results, the number of soil freezing days remained around 250 days, while the number of snow cover days was approximately 194 days. This reflects the different responses of frozen ground and snow to seasonal changes. Due to the higher heat capacity and slower heat conduction of the soil, the freezing and thawing processes are slower compared to snow. The simulation results also suggested a declining trend in both the number of frozen days and snow days during the study period. This likely reflects the impact of climate warming on seasonal frozen ground and snow cover.

Figure Captions

Figure S1. GXAJ model grid cell: (a) partitioning of runoff sources and (b) soil moisture and evapotranspiration in three soil layers.

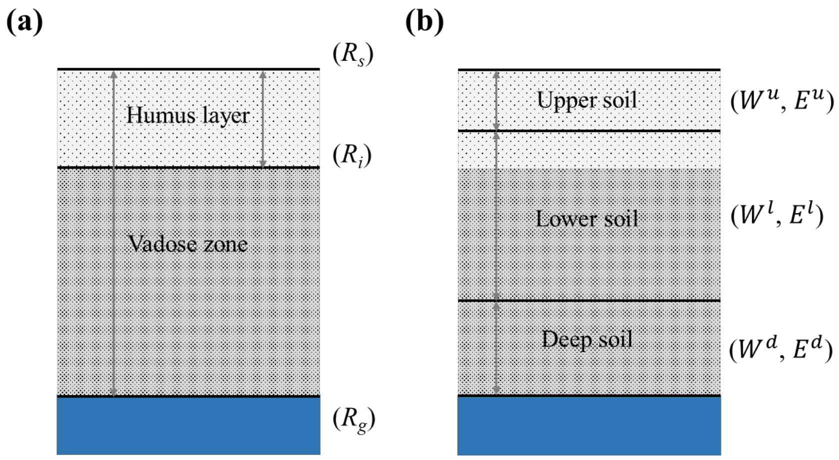
Figure S2. Snowmelt module grid cell: (a) runoff components and (b) calculation of soil water/ice content. R_s^* represents surface runoff influenced by frozen ground. W_i^u, W_i^l, W_i^d represent the ice content in the upper, lower, and deep soil layers, respectively, while W_w^d representing the water content in the deep soil layer.

Figure S3. Runoff components of the frozen ground module grid cell. R_s^* and R_i^* represent surface runoff and interflow components influenced by frozen ground.

Figure S4. Soil water/ice content and evapotranspiration of frozen ground module grid cells. $W_i^u, W_i^l,$ and W_i^d represent the ice content in the upper, lower, and deep soil layers, $W_w^u, W_w^l, and\ W_w^d$ represent the water content in the upper, lower, and deep soil layers.

Figure S5. Initial freezing and thawing dates of the surface soil at meteorological stations (a) 56034, (b) 56038, (c) 56146, (d) 56158, (e) 56251, (f) 56167.

Figure S6. Trends in the initial date, final date, and number of days for (a) soil freezing and (b) snow cover during the study period.



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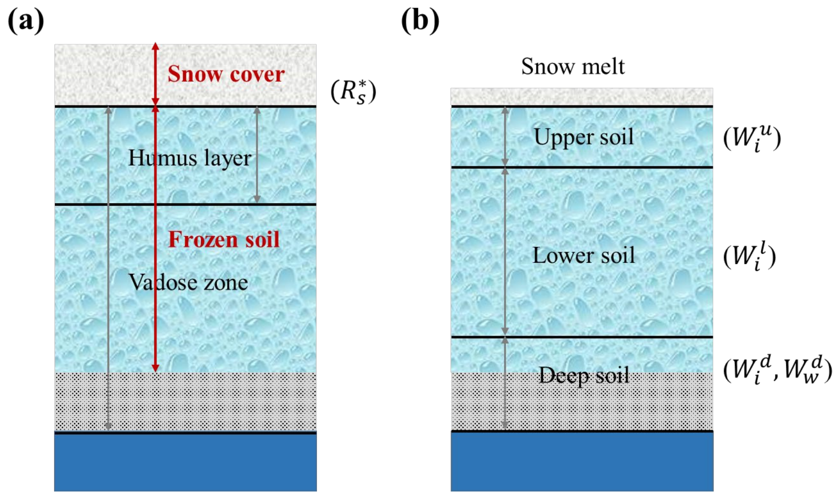


Figure S2. Snowmelt module grid cell: (a) runoff components and (b) calculation of soil water/ice content. R_s^* represents surface runoff influenced by frozen ground. W_i^u, W_i^l, W_i^d represent the ice content in the upper, lower, and deep soil layers, respectively, while W_w^d representing the water content in the deep soil layer.

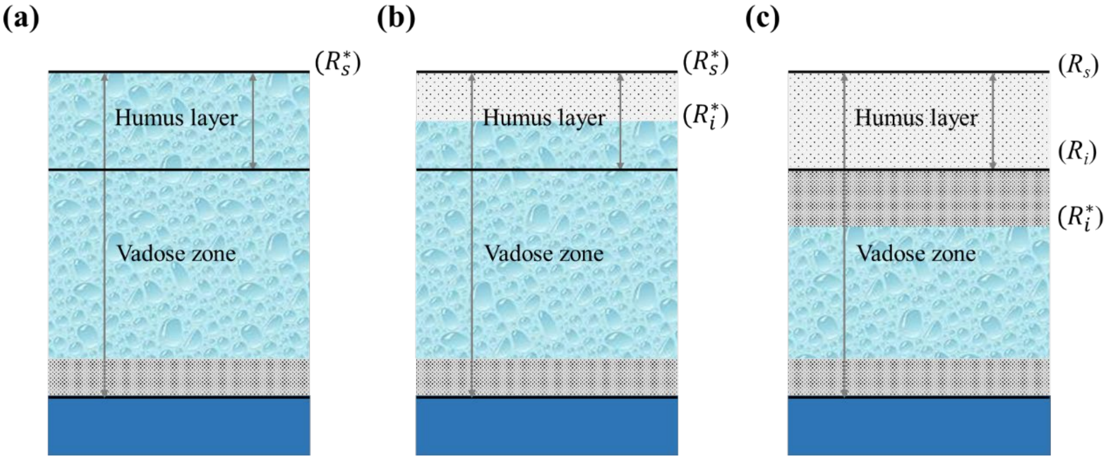


Figure S3. Runoff components of the frozen ground module grid cell. R_s^* and R_i^* represent surface runoff and interflow components influenced by frozen ground.

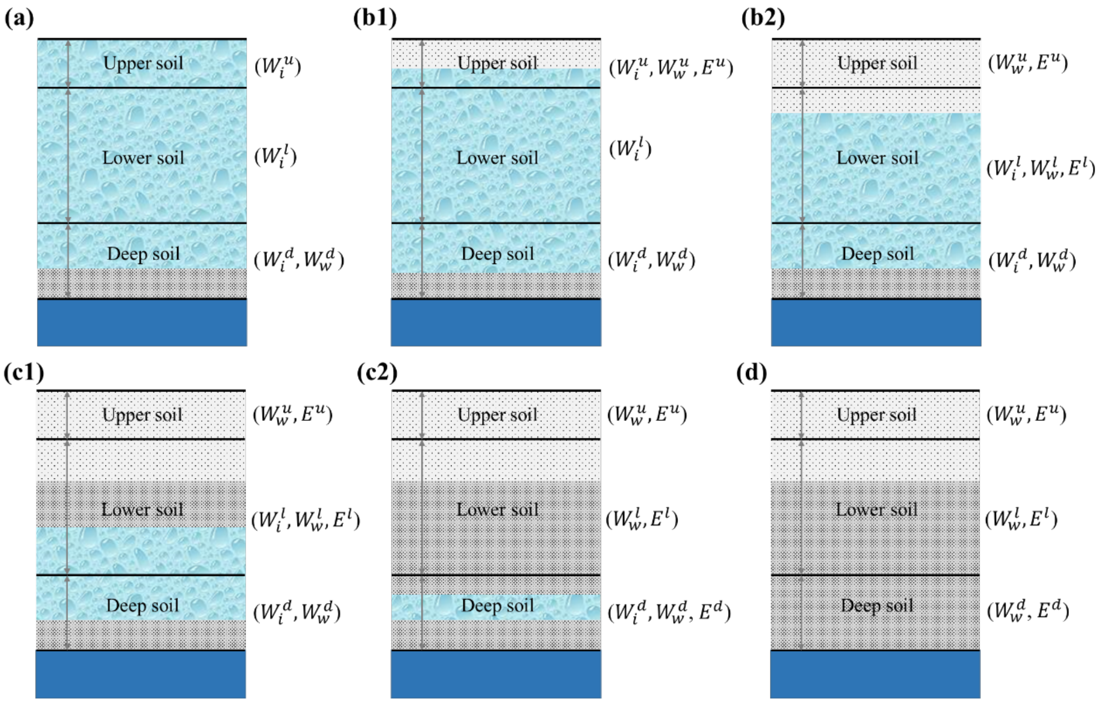
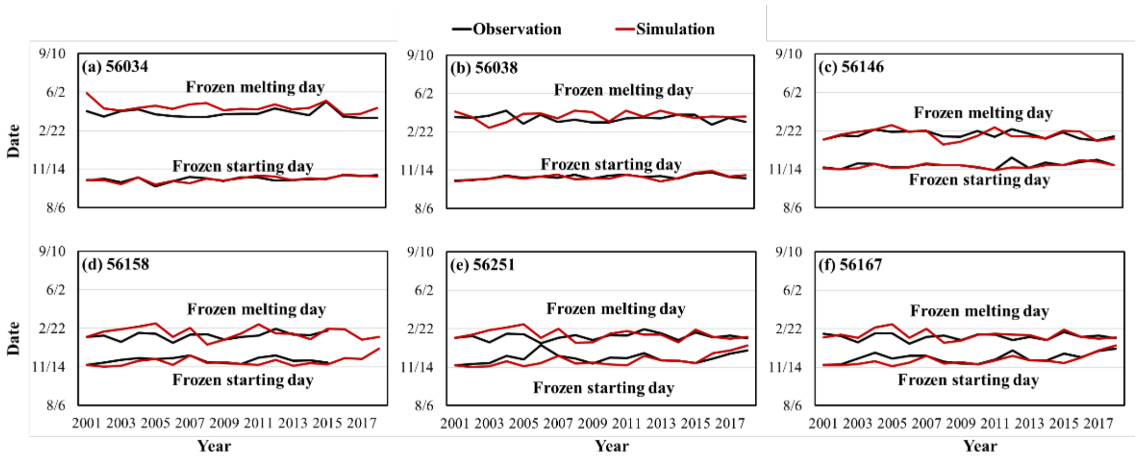


Figure S4. Soil water/ice content and evapotranspiration of frozen ground module grid cells. W_i^u, W_i^l, and W_i^d represent the ice content in the upper, lower, and deep soil layers, $W_w^u, W_w^l, and\ W_w^d$ represent the water content in the upper, lower, and deep soil layers.



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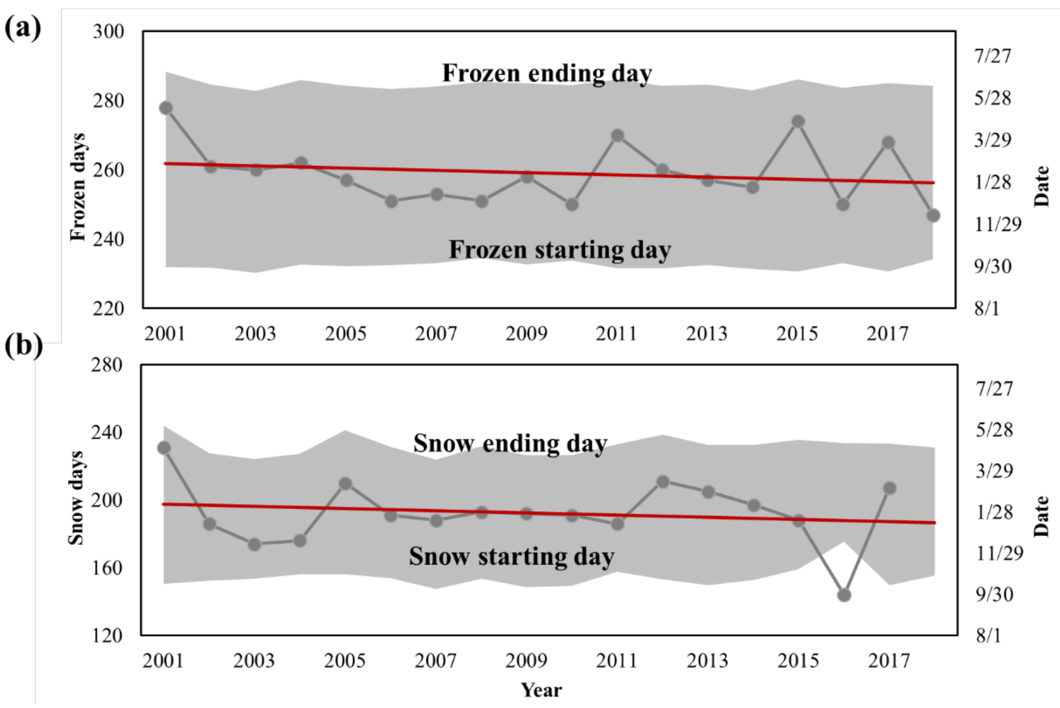

Figure S6. Trends in the initial date, final date, and number of days for (a) soil freezing and (b) snow cover during the study period.