Divergent runoff impacts of permafrost and seasonally frozen ground at a large river basin of Tibetan Plateau during 1960–2019

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Abstract

Since the 20th century, due to global warming, permafrost areas have undergone significant changes. The degradation of permafrost has complicated water cycle processes. Taking the upper Yellow River basin (UYRB) as a demonstration, this study discusses the long-term (1960–2019) changes in frozen ground and their hydrological effects with a cryosphere-hydrology model, in particular a permafrost version of the water and energy budget-based distributed hydrological model. The permafrost at the UYRB, with thickening active layer and lengthening thawing duration, has degraded by 10.8\%. The seasonally frozen ground has a more pronounced intra-annual regulation that replenishes surface runoff in the warm season, while the degradation of permafrost leads to a runoff increase. The occurrence of extreme events at the UYRB has gradually decreased with the degradation of frozen ground, but spring droughts and autumn floods become more serious. The results may help better understand the hydrological impacts of permafrost degradation in the Tibetan Plateau.

1. Introduction

The cryosphere includes various forms of glaciers, frozen ground, snow, and ice. It is one of the layers most vulnerable to human activities and climate change (Zhang et al 2003). Frozen ground is classified into permafrost and seasonally frozen ground (SFG). Permafrost accounts for about 13\% of the Earth’s area, and a quarter of the land in the northern hemisphere is overlain by permafrost (Biskaborn et al 2019). Although the overall global temperature is expected to rise no more than 2 °C until 2100 (Gao et al 2017), the permafrost regions have experienced climate warming more than twice the average global rate (Schuur et al 2015, Chadburn et al 2017, Guo et al 2018, Kou et al 2020). Climate warming causes widespread permafrost and SFG thawing (Schuur et al 2018). The degradation of frozen ground reduces soil moisture by increasing soil permeability and weakening the ability of the frozen ground area to maintain the water balance (Zona et al 2016). This change will have severe consequences for the ecosystem, hydrology system, infrastructure, carbon storage, and nitrogen dynamics (Zimov et al 2006, Ding et al 2017, Gao et al 2018, Hjort et al 2018, Jin et al 2019, Kou et al 2020, O’Neill et al 2020, Wang et al 2022).

In the past few decades, the relationship between permafrost and climate change has attracted significant attention. As the most critical high-altitude permafrost region in the world (Yao et al 2013, Zhang et al 2013, Zou et al 2017), the permafrost regions of the Tibetan Plateau (TP) respond more positively to climate warming (Wang et al 2012). Since the 1980s, the area of permafrost on the TP has shrunk severely. However, frozen ground is conducive to maintain the regional water cycle processes. The reduction of the frozen ground and the thickening of the active layer...
have fundamentally changed the groundwater storage, the land surface water cycle, and regional water resources. The hydrological relationship between TP and frozen ground degradation has gradually attracted more and more attention. At present, three research methods are used to analyze the hydrological effects of frozen ground: (a) use observation data for data analysis (Che et al. 2019, Zhao et al. 2019); (b) simulate with hydrological model simulations, such as variable infiltration capacity (VIC) (Cuo et al. 2015), Noah (Zheng et al. 2018), and the water and energy budget-based distributed hydrological model (WEB-DHM) (Wang et al. 2017, Qi et al. 2019), etc; (c) use empirical formulas and statistical analysis of other data (Qin et al. 2016, Shi et al. 2020).

The main results show that frozen ground degradation influences surface hydrological processes, such as degradation of SFG increasing baseflow (Qin et al. 2016), and permafrost degradation increasing runoff of rivers and lakes (Zhao and Sheng 2019). There have also been some in-depth studies on the hydrological effects of frozen ground. Shi et al. (2020) used the unary linear relationship to prove the degradation of permafrost and SFG would cause a decrease in the runoff at the upper Yangtze River Basin. Sun et al. (2020) used the Wasiim model to conclude that the permafrost degradation in the upper Yellow River basin (UYRB) will increase the runoff and baseflow. However, there are still some limitations, such as simplified research methods, limited research data, and unclear hydrological functions of various frozen ground types.

In summary, the current exploratory research methods for the hydrological effects of frozen ground and the amount of research data are relatively limited. And the hydrological functions of different frozen ground types have not yet been systematically analyzed and summarized. The permafrost version (WEB-DHM-pf) of the WEB-DHM (Wang et al. 2009) can accurately distinguish the types of frozen ground and assess the internal physical process correctly (Song et al. 2020). Clarifying the relationship between frozen ground and runoff is exceptionally significant to the TP, even to the Earth.

This study aims to clarify the runoff impacts of frozen ground (permafrost, and SFG) in the UYRB from the perspective of intra-annual and inter-annual regulation as well as extreme events in the UYRB from 1960 to 2019.

2. Description of study area

The UYRB, located in the northeast of the permafrost on the TP, is a transition zone of mid-latitude high-altitude SFG and permafrost throughout the basin (Jin et al. 2009, Luo et al. 2018a, Wang et al. 2018) (figure 1). There is no non-frozen ground area in the whole basin, and the proportion of permafrost in the upstream and SFG in the downstream is about 4:6 (data from Zou et al. 2017). The vegetation is dwarf and herbaceous and dominated by paludal and typical alpine meadows and steppes (Jin et al. 2009, Luo et al. 2014, 2020). The coverage and the thermal state of permafrost at the UYRB are proportional to the elevation (Jin et al. 2009, Luo et al. 2018b). Since the 1980s, permafrost is in a state of degradation with the increase in temperature and human activities. Studies have pointed out that the permafrost degradation at the UYRB was 11 628 km², accounting for 9.47% of the total basin area from 1970 to 2010 (Ran et al. 2018, Wang et al. 2018). The degradation of permafrost has become evident since the 1990s. The observed permafrost temperature at the depth of zero annual amplitude was reported to increase by 0.2 °C over the past decade (Luo et al. 2018). The most degradation of permafrost occurs in the southeast corner and the sporadic permafrost islands in the east of the UYRB. Given the complex geomorphological features and the prominent changing characteristics, coupled with the complete meteorological data and sufficient permafrost observations, the UYRB is one of the best regions for analyzing the formation and evolution history of high-altitude permafrost (Jin et al. 2010, Luo et al. 2018a, 2018b).

3. Method and data sets

In this study, we used the WEB-DHM-pf model, which takes into account the water phase changes in the unconfined aquifer and its hydrothermal exchange with the overlying soil. We used enthalpy as a variable in the energy balance equation instead of soil temperature, thus avoiding instability in the calculation of water phase changes. In addition, the boundary initial conditions for the bottom soil layer (over the unconfined aquifer) also newly consider the presence of soil ice in addition to soil temperature and soil moisture. A detailed description of the whole model and its functions are described in Song et al. (2020).

A resolution of 5 km of land use, vegetation, and meteorological data is required for the WEB-DHM-pf model. Soil temperature, soil moisture, and runoff observations for validation of the WEB-DHM-pf model are also included. The abovementioned data and study methods are described in Song et al. (2020). Figures 2(a) and (b) show the observed and simulated daily discharge at the UYRB (Tangnaihai gauge) during 1981–1985 (calibration period) and 1986–2019 (validation period), and the monthly discharge from 1981 to 2019, respectively. The Nash–Sutcliffe efficiency (Nash; Zeybek et al. 2018) and relative bias error (RBE) values were 0.81 and −4.12% for the calibration period, and 0.74 and 5.50% for the validation period, while they were 0.86 and 3.90% for the monthly discharge during 1981–2019. These results have demonstrated that the
new model can reproduce the inter-annual and intra-annual variations in the observed river discharge at the UYRB.

Figure 2(c) shows the comparison of the simulated basin-averaged monthly evapotranspiration (ET) and the reference ET (calculated by water balance method) during 2003–2015 at the UYRB. The Nash, BIAS, and root-mean-squared error (RMSE) values were 0.77, 2.67 mm, and 15.23 mm, respectively. Using basin-averaged ET as the evaluation criterion, the model can accurately reproduce the ET variation from 2003 to 2015 in the UYRB. Simultaneously, the soil temperature and moisture from 0 to 250 cm depth were also well validated, including three SFG sites and one permafrost site (figures A1–A5) (Song et al 2020). Results showed that the model can reasonably describe the contours of soil temperature and soil moisture at the point scale and can characterize the maximum freezing depth and the hydrothermal physical processes of permafrost (including the zero-curtain phenomenon) (Song et al 2020).

The WEB-DHM-pf hydrological model is not only effective in simulating the runoff changes and reference ET at the UYRB but also can accurately distinguish the spatial distribution of frozen ground types at the basin scale, providing an effective tool for long-term change analysis of frozen ground.

4. Results and discussion

4.1. Changes in the frozen ground over the past 60 years

Soil temperatures in the UYRB have increased significantly since the 1960s. The rate of temperature warming in the soil layer of 2 cm was $0.17 ^\circ C/10a$, and that of 200 cm was $0.19 ^\circ C/10a$, (figure 3(a)). The change of soil temperature in the ground surface is closely related to the air temperature trends. The ET at the ground surface also becomes more prominent, increasing the fluctuation of surface soil temperature. Meanwhile, the soil temperature of the shallow layer (200 cm) shows an increasing trend, and the rate of warming is higher than that of the ground surface. This further confirms that the frozen ground in the UYRB has a warming and thawing trend. Along with the warming of the soil layers, the soil absorbed more energy and the ground ice kept melting, which in turn changed the soil moisture and ice contents in the UYRB. Figure 3(b) shows the long-term changes of the basin-averaged soil moisture and ice content (sum of 0–2.0 m) in the UYRB from 1960 to 2019. The soil moisture content increased at a rate of 0.004 m$^3$ m$^{-3}$/10a ($p < 0.05$), and the soil ice content decreased at a rate of $-0.028$ m$^3$ m$^{-3}$/10a ($p < 0.05$) during the 60 years.
The upper reaches of the UYRB are dominated by permafrost, and the lower reaches are covered by SFG. The maximum freezing depth of SFG decreased significantly at $-0.045 \text{ m/10a} (p < 0.05)$ during 1960–2019, while the active layer thickness of permafrost increased at a rate of $0.011 \text{ m/10a} (p > 0.1)$ (figure 3(c)). The thaw duration in the SFG was up to 230 d yr$^{-1}$, almost one month more than the thaw duration in the permafrost. The thaw duration of SFG and permafrost increased with thaw rates of $3.8 \text{ d yr}^{-1} (p < 0.05)$ and $1.8 \text{ d yr}^{-1} (p > 0.1)$, respectively (figure 3(d)). Since the 1960s, the permafrost area in the UYRB has been decreasing. The degradation of permafrost mainly has occurred in the southeastern UYRB around the Gyaring and Ngöring Lakes. The island and sheet-shaped permafrost in the interior of the basin also gradually degraded to SFG (figure 3(e)). The degradation rate of permafrost area was $-2142.9 \text{ km}^2/10a (p < 0.05)$, and the total area of permafrost degradation is $13,050 \text{ km}^2$ during the 60 years, which accounts for 10.77% of the basin area.

Overall, the increase in soil temperature in the UYRB has led to a decrease in soil ice during the last 60 years. Part of the permafrost has evolved into the SFG. The area of permafrost has degraded by 10.77% of the basin. The active layer has thickened,
the maximum freezing depth of SFG has decreased, and the thawing period has continued to extend.

### 4.2. Impacts of frozen ground on runoff

As mentioned above, since 1960, the UYRB has warmed and frozen ground has thawed. The thickening of the active layer and the accelerated melting of ground ice will cause changes in surface hydrological conditions, making the water cycle processes in frozen ground regions more complicated. On the one hand, the migration of unfrozen water during freezing will lead to more unfrozen water migration to the upper limit of permafrost. On the other hand, the increased thickness of the active layer leads to the release of a large amount of frozen water from the melting of the thick layer of subsurface ice at the bottom (Zhao et al. 2000, 2019). Overall, the interconversion of soil ice, soil moisture, and unfrozen water during permafrost degradation makes the physical processes within the permafrost increasingly complex. Therefore, this section clarifies the relationship between frozen ground and surface runoff from seasonal runoff, long-term runoff, and hydrologic extremes.

In this paper, three experiments were designed. First, frozen ground exists and degrades in the model (WEB-DHM-pf), which implies that hydrothermal exchange processes occur within the soil and between it and ground ice; second, frozen ground exists in the model but does not degrade (WEB-DHM-pf_T1960), which implies that only seasonal hydrothermal exchange processes occur within the soil and between it and ground ice, without the complex physical process of degrading permafrost into SFG; third, frozen ground does not exist in the model (WEB-DHM-s), which implies that no ground ice exists in the soil and only simple soil hydrothermal transfer occurs. Also note that in the T1960 test, we assume that the temperature is constant, i.e. the permafrost is constant. By analyzing the soil temperature of the

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**Figure 3.** (a) Simulated long-term changes of basin-averaged soil temperature (2 cm and 200 cm depth); (b) soil ice and soil moisture content (sum of 0–200 cm); (c) active layer thickness of permafrost and maximum freezing depth of seasonally frozen ground; (d) inter-annual spatial changes of permafrost and seasonally-frozen ground at the UYRB during 1960–2019; and (e) spatial distribution and changes of permafrost in 1960s and 2010s.
2 cm of permafrost in T1960, we found that the rate of increase was negligible. Therefore, compared with the trend of other tests, it can be concluded that the permafrost in T1960 is constant.

4.2.1. Seasonal regulation of runoff

In this section, the models with or without frozen ground processes (WEB-DHM-pf and WEB-DHM-s) were used to explore the seasonal regulation of the presence of frozen ground on river runoff. Figure 4(a) provides a comparison of the simulated monthly mean discharge at Tangnaihai hydrological station over 1960–2019. During the warm season (June–September), thawing frozen ground contributes to an increase in runoff. During the other seasons (from October to the following May), the presence of frozen ground leads to a decrease in the runoff. To clarify the seasonal regulation of surface runoff by permafrost and SFG, grid runoff changes in SFG (figure 4(b)) and permafrost areas (figure 4(c)) simulated by WEB-DHM-pf and WEB-DHM-s were further compared.

Regarding the permafrost, the positive regulation of runoff is most pronounced in June, while the permafrost generally decreases runoff in the other months (figure 4(c)). In June, when the permafrost zone in the high-altitude has not yet thawed (or has just begun to thaw), the permafrost still acts as a specific ‘water barrier’. However, at this time, the snow and glaciers have started melting and the
precipitation begins to increase, both of which are difficult to infiltrate into the soil and thus preferentially flow into the main channel of the UYRB, making the runoff significantly higher. During the soil thawing period, the active layer of permafrost acts as ‘water storage’, allowing more surface runoff to infiltrate into the deeper soils and participate in the groundwater process. Therefore, the role of permafrost in the seasonal regulation of surface runoff is mainly the function of water barrier and water storage.

4.2.2. Long-term impacts on runoff

In this section, we consider the model running with (WEB-DHM-pf) or without (WEB-DHM-pf_T1960) warming to explore the long-term regulation of the presence of frozen ground on surface runoff. Figure 4(d) shows a comparison of simulated annual discharge at Tangnaihai hydrological station over 1960–2019. The runoff simulated by the WEB-DHM-pf_T1960 (that keeps the air temperature inputs as those in 1960) increases at a rate of 10.37 m³ s⁻¹/10a (p > 0.1). In contrast, the runoff simulated by the WEB-DHM-pf (under warming as reality) decreases at a rate of 10.12 m³ s⁻¹/10a (p > 0.1), reinforcing that the degradation of frozen ground can accelerate the reduction of runoff. The runoff difference between the two models with or without the global warming (QWEB-DHM-pf − QWEB-DHM-pf_T1960) is also displayed for reference. If the trend in runoff difference is negative, then the frozen ground change contributes to the decrease of runoff; while if it is positive, the frozen ground change contributes to the runoff increase. From 1960 to 2019, the runoff difference shows a significantly decreasing trend with a rate of −21.48 m³ s⁻¹/10a (p < 0.05), indicating that frozen ground degradation causes continuous infiltration of surface runoff and decreases the river runoff.

The long-term changes in surface runoff due to different frozen ground types (permafrost and SFG) are also given in figures 4(f) and (e). The long-term degradation of SFG had no significant effect on surface runoff (figure 4(e)). The simulated runoff from WEB-DHM-pf_T1960 and WEB-DHM-pf shows decreasing trends with rates of −1.19 m³ s⁻¹/10a and −1.28 m³ s⁻¹/10a, respectively. Still, the latter is smaller than the former, which indicates that the SFG degradation also contributes to reducing surface runoff. However, the runoff difference is too small to demonstrate the long-term effect of SFG.

The impact of permafrost degradation on runoff is more pronounced than SFG (figure 4(f)). The simulated runoff from WEB-DHM-pf_T1960 increases with a rate of 1.02 m³ s⁻¹/10a (p < 0.05). On the contrary, the simulated runoff considering the degradation of frozen ground (WEB-DHM-pf) shows a weak decreasing trend within interdecadal scales, so there is a significant difference between the two trends. This difference establishes that the degradation of permafrost contributes to the drop in surface runoff. The continuous degradation of permafrost increases the storage capacity of the system, slowing runoff generation. The degradation of permafrost in the UYRB resulted in a significant decrease in surface runoff at a rate of 1.03 m³ s⁻¹/10a. Figure 4(f) also shows that permafrost degradation in the UYRB began to change significantly in the late 1990s (or early 21st century). And that the hydrological effects of permafrost gradually became prominent around 1995.

From the whole space change, when the temperature remains constant, the surface runoff in the entire basin has shown an increasing trend, with the most noticeable increase in the interior of the basin and a slight decrease in the southeast corner of the UYRB (figure 4(g)). As the temperature continues to rise and the permafrost degrades, the runoff in the upper reaches of the basin (permafrost area) slightly increases, while the runoff in the lower reaches of the basin (SFG area) decreases (figure 4(h)). In general, the degradation of frozen ground during the past 60 years has a negative impact on the surface runoff of the UYRB. The most remarkable area is in the interior UYRB: all types of frozen ground have contributed to the reduction of surface runoff (figure 4(i)). In addition, the degradation of the southeast corner and the north of the SFG area has a weak positive impact on runoff. It promotes an increase in runoff, but the effect is not significant due to the small scale. The local degradation of the sister lakes (Gyaring and Ngöring) in the permafrost region positively impacts surface runoff, mainly releasing outflow to replenish surface runoff.

4.2.3. Hydrological extremes

The influence of frozen ground on hydrological extremes was explored at Tangnaihai hydrological station. This research focuses on the analysis of 95% quantile (Q95) and 5% quantile (Q5) runoff, where Q95 represents the annual runoff that is greater than 95% of the runoff from 1960 to 2019, and Q5 represents the runoff that is less than 5% of the runoff from 1960 to 2019. Figure 5 shows the long-term change of Q95 and Q5 quantile runoff from the WEB-DHM-pf simulation relative to the WEB-DHM-pf_T1960 simulation (σ = (QWEB-DHM-pf − QWEB-DHM-pf_T1960) / QWEB-DHM-pf_T1960 × 100%). The relative change characterizes the effect of frozen ground changes on Q95 and Q5 quantile runoff. As figure 5(a) shows, the degradation of frozen ground contributed to the decrease in Q95 quantile runoff and Q5 quantile runoff during 1960–2019, demonstrating that the flood peak weakens but the drought will continue to intensify under the effect of the degradation of frozen ground.
With the warming of the climate, the intensity of spring droughts and spring floods has increased (figure 5(b)), and the spring runoff of the UYRB has become more and more extreme. The soil gradually melts in spring, and the soil moisture released by the frozen ground is not enough to make up for the ET, which together leads to a decrease in surface runoff. The most obvious hydrological impact of frozen ground degradation in summer is to weaken the flood peak, but an inevitable drought also accompanies it (figure 5(c)). The ground ice existing in SFG and the active layer of permafrost has entirely melted in summer. The thawed soil has a greater storage, storing more water and reducing surface runoff in summer.

In autumn (figure 5(c)), frozen soil plays a role in water storage, storing melt-water from snow and glaciers, and forming underground reservoirs through precipitation and soil moisture generated by the thawing soils. As the UYRB continues warming, the active layer thickens, and the thawing period of frozen ground is prolonged. More melting of ground ice participates in groundwater runoff. In addition, during a longer thawing time, more surface water seeps into the deeper soils. On the whole, the capacity of groundwater reservoirs continues to increase. To a certain extent, it is forced to supplement the surface runoff in low-lying areas, but it promotes the infiltration of surface runoff to form groundwater runoff. These physical processes make the surface runoff in autumn gradually flatten under the regulation of frozen ground. Meanwhile, the extreme runoff in winter is consistent with the change in spring, but the intensity of extreme events is not significant due to the low baseflow in winter.
5. Conclusions

Three permafrost–hydrology simulations have been performed in this study, producing a lot of soil data (e.g. soil temperature, soil moisture content, and soil ice content) and hydrological data (e.g. grid ET and grid runoff). The process of frozen ground degradation in the past 60 years (1960–2019) was analyzed in the UYRB. The impact of permafrost and SFG degradation on surface runoff in the UYRB was discussed. The study aims to reveal the spatiotemporal changes of frozen ground in the UYRB and the influence mechanism of frozen ground on runoff generation under rapid regional warming. Exploring the hydrological functions of frozen soil from the perspective of large-scale watersheds provides particular support for clarifying the hydrological effects of frozen ground. The main conclusions of this study are as follows:

(a) From 1960 to 2019, the area of permafrost receded by a total of 13 050 km², accounting for 10.8% of the UYRB. The soil temperature and soil moisture content in the UYRB increased, while the soil ice content decreased. The active layer of permafrost continues to thicken. The maximum freezing depth of SFG becomes significantly decreased. The thaw duration in the whole basin continues to extend, and SFG responds more positively to climate warming.

(b) In the warm season, the presence of frozen ground tends to increase the runoff, but reduces the runoff in the cold season. Compared with permafrost, SFG has more obvious seasonal regulation on the runoff.

(c) On the inter-annual scale, permafrost degradation has a more significant impact on surface runoff. The considerable water storage capacity of permafrost causes the decrease of surface runoff; the degradation of SFG only has a very weak negative impact on runoff and can be ignored. Climate warming leads to the degradation of frozen ground and changes the spatial pattern of surface runoff at the UYRB. The degradation of frozen ground decreases runoff.

(d) The degradation of frozen ground has led to the reduction of Q95 and Q5 runoff. In the UYRB, the flood peak (Q95) weakens, but drought (Q5) will continue to intensify under regional warming, which is most obvious in summer. The extreme hydrological events in spring and winter have gradually sharpened, while the runoff in autumn has gradually flattened with the degradation of frozen ground.

In recent years, global warming and permafrost degradation have enhanced the water storage and replenishment function of soil on the frozen ground area. The impact of frozen ground on surface runoff has become more complex, and there has been no systematic analysis and generalization between frozen ground and surface runoff. This paper has clarified the effects of different types of frozen ground on surface runoff, e.g. the impacts of frozen ground on the intra-annual runoff changes, the inter-annual runoff changes caused by the degradation of frozen ground, and whether the degradation of frozen ground will cause extreme hydrological events. The above results help to understand the impacts of the loss of ground ice on hydrology for future exploration and research on the hydrological effects of frozen ground.

Data availability statements

The GRACE data can be downloaded from https://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/. The modelled water balance data at the upper Yellow River basin (gridded precipitation, simulated evapotranspiration, and runoff) can be downloaded from https://doi.org/10.11888/Hydro.tpdc.270957. The runoff observations of the Yellow River that are administrated by the Ministry of Water Resources in China (MWRC), can be accessed from the published Hydrological Yearbooks of China in the National Library of China (www.nlc.cn/newen/).

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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Appendix

Figure A1. Temporal variations in (a) air temperature anomaly, (b) soil temperature, (c) soil moisture, and (d) soil ice in the soil layer at the ELH site (seasonally frozen ground) from 1981 to 2017. The temperature anomaly is calculated based on the 1981–2017 average (Song et al 2020).

Figure A2. Temporal variations in (a) air temperature anomaly, (b) soil temperature, (c) soil moisture, and (d) soil ice in the soil layer at the CLP site (permafrost) from 1981 to 2017. The temperature anomaly is calculated based on the 1981–2017 average (Song et al 2020).
Figure A3. Observed and simulated (a) soil temperature and (b) soil moisture at 5 cm soil depth at the CST_01 and NST_03 sites covered by SFG (Song et al. 2020).

Figure A4. Simulated (a), observed (b), and difference (c) isotherms of soil temperature at the ELH site (SFG) in the UYRB. The difference is observation minus simulation (Song et al. 2020).
Figure A5. Observed (a) and simulated (b) isotherms of soil moisture, as well as their difference (c = a − b) at the permafrost CLP site in the UYRB (Song et al. 2020).
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