General comments

Comments 1: The authors present a modeling study on the hydrological impacts of snow and frozen ground dynamics in a topographically complex basin. The topic of cryospheric changes and their impacts on hydrology is both significant and timely. However, the authors should address several key issues in the current manuscript to enhance its quality before it can be considered further.

I think the novelty of this study is not sufficiently distinctive or well-highlighted. There have already been numerous modeling studies on snow and frozen ground dynamics in the Tibetan Plateau region, both the basin-scale and regional-scale studies are conducted. Moreover, the models employed in previous studies provided more advanced representations of snow and frozen ground processes, particularly in terms of frozen ground dynamics, compared to the model used in this study. Therefore, the authors need to consider how to better emphasize the unique contributions of this study in comparison to prior research.

Response 1: Thank you for your thoughtful evaluation and constructive feedback. We appreciate your comments regarding the novelty of our study, which have prompted us to clarify and highlight the unique contributions of our research more effectively.

We believe the uniqueness of this study is reflected in the following aspects:

- **The hydrological impacts of snow and frozen ground in large basins**

As you mentioned, the impacts of snow and frozen ground on runoff processes have been confirmed in many small-scale studies. However, we would like to further clarify that significant knowledge gaps remain regarding the complex and less well-understood effects of seasonally frozen ground (SFG) on runoff in large-scale basins (e.g., Ala-Aho et al., 2021). Therefore, at such a large scale, the question of how model complexity influences the ability to capture key hydrological processes and produce sufficiently accurate runoff simulations under the presence of snow and SFG remains relatively unresolved. This study aims to fill this knowledge gap through a systematic analysis of the performance of models with different levels of complexity. We will further emphasize this point in the revised title, discussion, and conclusion sections.

- **A simple and data-efficient snow and freeze-thaw coupling method**

A key innovation of this study is the integration of the physical mechanisms of snowmelt and freeze-thaw cycles into the hydrological model, enabling the quantitative analysis of the impacts of snowmelt and frozen ground on runoff, soil moisture dynamics, and evapotranspiration. The developed snow and freeze-thaw coupling module is physically meaningful, requires relatively few additional parameters, and has low dependence on input data. This feature is particularly important for cold regions, where data is often limited.

- **Quantitative assessment of the impacts of SFG on hydrological processes in large basins**

Given the significant knowledge gaps regarding the large-scale impacts of SFG on runoff, another novel aspect of this study lies in the systematic comparison of simplified models (without coupled snow-SFG modules or only considering snow processes) and extended models that include the combined effects of snow and SFG. Such comparisons enhance our understanding of the extent to which SFG processes play a role in large-basin runoff and provide guidance on the necessary level of model complexity. For example, our quantitative results indicate that SFG can significantly increase surface runoff in large basins during cold months (by 39%-77% compared to models that ignore SFG) while reducing interflow and groundwater runoff. These findings will be further highlighted in the revised introduction and discussion sections.

- **Combining hydrological cycle process understanding with practical applications**

Through the analysis and quantification of frozen soil depth and its spatiotemporal distribution impacts on hydrological processes, this study reveals the complex feedback mechanisms of frozen ground on hydrological systems. These analyses not only deepen our understanding of the dynamic interactions between snow, freeze-thaw processes, and hydrological processes but also provide critical references for predicting hydrological changes in cold mountainous regions under future climate change scenarios.

We will further emphasize these unique contributions in the revised manuscript. Once again, we sincerely thank the reviewer for your valuable comments.

Specific comments

Comments 2: In Figure 3c, it is evident that a significant portion of the study area is covered by permafrost. However, the Stefan model mentioned in the methodology is designed to model seasonal frozen ground. Did the authors separately account for the dynamics of permafrost in their study? If not, this could be a critical limitation that needs to be addressed or clarified.

Response 2: Thank you for highlighting this important aspect. As shown in Figure 3c, the study area is dominated by seasonal frozen ground, while permafrost accounts for less than 10% and is sparsely distributed along the edges of the study area. Therefore, our study primarily focuses on seasonal frozen ground, and the improved module is more efficient in regions dominated by seasonal frozen ground. The simulation results proved that the model achieves high accuracy in these areas.

However, we acknowledge that even a small portion of permafrost may influence hydrological processes and runoff simulations. We will further discuss this potential impact, as well as the limitations of the proposed model in permafrost regions and the uncertainties introduced by this limitation, in the revised manuscript. Thank you for bringing this to our attention, which will help us further strengthen our study.

Comments 3: Line 272-275: How was this threshold 30cm determined? Was a sensitivity analysis conducted to assess the impact of this threshold on the results? Providing such an analysis would help evaluate the robustness of the study's findings.

Response 3: Thank you for the valuable question! The 30 cm threshold mentioned in Lines 272-275 is based on findings from previous studies. Many studies have explored different snow depth thresholds. For example, Brooks et al. (1995, 1999) and Cline (1995) suggested that when snow depth reaches 30-40 cm, air temperature is unlikely to significantly affect ground temperature. Building on this, Hill (2015) proposed a conceptual model indicating that thick snow cover (>30 cm) effectively insulates the ground, keeping it thawed year-round and enabling groundwater recharge. This also leads to an earlier hydrological response compared to thin snow cover (<30 cm), where the ground may remain seasonally frozen during the snowmelt season, limiting groundwater recharge and resulting in a delayed hydrological response later in the summer.

In our study, we adopted Hill's (2015) proposed 30 cm threshold for snow depth, supported by the above literature. We will include the relevant references and further elaborate on this background in the revised manuscript. We sincerely thank the reviewer for highlighting this important point!

Comments 4: In Table 3, the authors utilized several data products from other studies. However, the accuracy of these datasets, particularly the snow depth data, which is critical for this study, has not been clarified.

Response 4: Thank you for pointing out this important aspect. We acknowledge that the accuracy of the datasets used, particularly the snow depth data, is critical for this study. In the revised manuscript, we will include additional details about the accuracy and validation of the data products utilized, especially the snow depth dataset. Furthermore, we will expand the discussion section to address the uncertainties introduced by the snow depth data and their potential impact on our findings.

We sincerely appreciate the reviewer's insightful suggestion, which will help improve the robustness and clarity of our study.

Comments 5: Line 309-404: In points with high snow depth, there are significant discrepancies between the model results and the remote sensing data. The authors should investigate the underlying causes of these differences.

Response 5: Thank you for your valuable comment. We used the SNOW17 model to simulate snow depth and compared the results with remote sensing data. We noticed discrepancies between the model results and the remote sensing data in areas with high snow depth. One potential reason is that hydrological processes in areas with high snow depth are more complex. The model employs simplified parameterization methods to simulate snow accumulation and melting processes in these regions, which may not fully capture the spatial heterogeneity of snow processes. Additionally, remote sensing data may have limitations in capturing extreme snow depths, such as signal saturation or terrain occlusion in mountainous areas, which could introduce errors.

These factors may also explain the lower simulation accuracy of spring runoff shown in Figures 6 to 8. However, despite the discrepancies in areas with high snow depth, the calibration and validation results demonstrate relatively low RMSE and BIAS values, indicating that the model performs well overall in simulating snow depth dynamics, particularly in areas with moderate snow depth. Furthermore, the improved model shows significant advancements in simulating snowmelt runoff compared to the original model.

We acknowledge that snowmelt is a complex hydrological process, and under limited data conditions, we strive to utilize available observational and remote sensing data to simulate the snowmelt process with higher accuracy. While certain limitations and errors are inevitable, we believe that such efforts are meaningful and valuable, particularly in cold regions where data scarcity presents significant challenges.

In the revised manuscript, we will further investigate and discuss the potential causes of these discrepancies, including the limitations of both the remote sensing data and the model itself. Additionally, we will include a more comprehensive discussion in the uncertainty analysis section to address these issues and propose directions for future improvements.

Comments 6: Line 412:415: For the simulation of frozen ground processes, verifying only the accuracy of the initial freeze and initial thaw dates is far from sufficient. It is also essential to validate the simulated soil temperature and soil moisture (including liquid water content and soil ice content). These variables are key to understanding how freeze-thaw processes influence basin hydrology. Therefore, the authors should provide validation results for these variables to demonstrate the reliability of the study's findings.

Response 6: Thank you for your valuable comments. Due to the lack of measured frozen ground depth data, soil temperature, and soil moisture (which is common in most cold regions), we are currently unable to directly validate the simulated frozen ground depth and freeze-thaw processes. Therefore, this study primarily uses available surface temperature data to validate the initial freeze and thaw dates, thereby indirectly supporting the reliability of the simulated freeze-thaw processes, a method that has been supported by several studies.

To further assess the reliability of the model, we compared the spatial distribution of the maximum frozen ground depth simulated in this study with the 2000s Tibetan Plateau Permafrost Dataset (1961–2020). The comparison results show a high level of consistency in both spatial distribution patterns and magnitudes, with a correlation coefficient of 0.89. These results provide additional validation support for the model, which we will present in the revised manuscript.

We also acknowledge that using surface temperature to validate the freeze-thaw process introduces some uncertainty, as the freeze-thaw process propagates from the surface downward, and surface temperature data only partially reflect the dynamics of deeper frozen layers. To address this, we will expand the discussion section to further analyze this uncertainty and its potential impacts. At the same time, utilizing existing data resources to validate hydrological processes in data-scarce regions remains highly meaningful. This approach provides a strong foundation for supporting the model’s applicability in regional assessments.

Comments 7: The ‘Results’ section is too brief and lacks depth in describing the characteristics of snow and frozen ground changes and their hydrological effects. For instance, there is insufficient discussion on how frozen ground processes alter soil temperature and moisture conditions, thereby influencing hydrological processes, as well as how snow changes directly impact runoff. Additionally, the manuscript does not adequately address how snow affects frozen ground processes and thereby indirectly impacts hydrology. Moreover, compared to the analysis of the differences in runoff simulations using various modules, I believe it would be more meaningful to explore how the synergistic changes in snow and frozen ground under climate change influence runoff in the study area during the past decades.

Response 7: We sincerely thank the reviewer for the valuable suggestions. We fully acknowledge your recommendations and will expand the "Results" section in the revised manuscript to provide a more comprehensive description of the characteristics of snow and frozen ground changes and their impacts on hydrological processes. In the current study, we primarily focused on the influence of frozen ground on soil moisture conditions, and this part will be further supplemented in the revised manuscript. Additionally, we will deepen the discussion in the "Results" section to explore how snow changes directly affect runoff and how snow indirectly influences hydrology through its impact on frozen ground processes.

Regarding your suggestion to investigate the impact of synergistic changes in snow and frozen ground under climate change on runoff over the past decades, we fully recognize the importance of this research direction. However, the main objective of this study is not only to analyze differences in runoff simulation using different modules but also to develop and evaluate an enhanced hydrological model suitable for cold regions. This model integrates snowmelt and freeze-thaw processes, features modular design, is computationally simple, and has wide applicability. Furthermore, we quantitatively analyzed the contribution of snowmelt to runoff generation and the impact of frozen ground on soil conditions, runoff components, and evapotranspiration. The primary focus of this study is to verify the applicability and reliability of the developed model, providing a practical tool for hydrological and climatic assessments and predictions in cold mountainous regions. By quantifying the roles of snow and frozen ground in hydrological processes, our study also contributes to a deeper understanding of the complex hydrological processes in cold regions. It is not, however, aimed at systematically analyzing the long-term impact of climate change on runoff. We will further clarify this research objective in the revised manuscript.

Due to the lack of observed runoff data in the study area, our current analysis is limited to hydrological simulations over a 19-year period from 2000 to 2018. More extensive observational data would be required for analyzing runoff changes on a longer temporal scale.

Once again, we sincerely thank you for your valuable suggestions. We will further clarify and expand the relevant discussions in the revised manuscript to better address your feedback.

Comments 8: In the 'Discussion' section, the authors should focus on how their findings represent an advancement over previous research and then call back to the research questions outlined in the Introduction. Rather than including an extensive literature review, the discussion should emphasize the novel contributions of this study and its implications for the field.

Response 8: Thank you for the valuable suggestion. In the revised manuscript, we will restructure the "Discussion" section to better align with the research questions outlined in the Introduction and to emphasize the novel contributions of this study. Specifically, we will:

- Highlight the key findings of this research and explain how they advance the field beyond previous studies. For instance, we will focus on the development and application of the GXAJ-S-SF model, which integrates snowmelt and freeze-thaw processes to improve hydrological simulations in cold regions, and discuss its significance.
- Streamline the discussion by reducing the emphasis on literature review and instead focus on the unique contributions of this study, such as quantifying the impacts of snow and seasonally frozen ground on runoff, evapotranspiration, and soil moisture dynamics.
- Clearly articulate the broader implications of our findings for hydrological modeling, water resource management, and climate change impact assessments, particularly for cold mountainous regions.

By incorporating these adjustments, we aim to provide a more focused and impactful narrative that underscores the significance of our findings and their relevance to the field.