Author's Response to Reviewer Comments

Dear Prof. Xiao,

Many thanks for taking the time to read our manuscript carefully and for your constructive comments on our manuscript. We found your suggestions quite useful for improving the clarity and impact of our work. Here is our point-by-point response.

Reviewer's comment 1 (Title precision):

"The title uses the broad term 'Snow-Temperature Interactions,' which does not accurately reflect the actual variables analyzed in the paper. The study focuses specifically on snow depth and land surface temperature, not on snow or temperature in a general sense. I recommend revising the title to a more precise expression, such as 'Mechanisms and Patterns of Snow Depth and Land Surface Temperature Interactions in Arid Mountains: Coupling Coordination and Lagged Responses Across Xinjiang, China.' Similar precision should be applied consistently throughout the abstract and the main text to avoid misleading readers about the core study object."

Our Response to comment 1:

We fully agree. The current title is indeed too general. We will revise the title to be more precise. Following your suggestion, we propose a new title: "**Mechanisms and Patterns of Snow Depth and Land Surface Temperature Interactions in Arid Mountains: Coupling Coordination and Lagged Responses Across Xinjiang, China**"

We will also check the abstract and the main text to ensure that the terms "snow depth" and "land surface temperature" (rather than generic "snow" or "temperature") are used consistently. Thank you for pointing this out.

Reviewer's comment 2 (Scientific significance and practical value):

"The scientific significance and practical value of the study are not sufficiently highlighted. Readers need to understand, from the outset, what concrete scientific advances or practical improvements can be achieved by quantifying the coupling

coordination and time-lagged responses between snow depth and land surface temperature. For example, does this approach help quantitatively identify changes in snowpack thermal inertia, improve the timing of snowmelt predictions, provide empirical constraints for snow parameterization schemes in land surface models, or establish critical thresholds for water resource management in arid regions? I suggest that the authors add a concise, forceful paragraph at the end of the Introduction and another at the beginning of the Conclusions to clearly articulate the unique contributions and specific application scenarios of this work, rather than dispersing these points vaguely across multiple sections.”

Our Response to comment 2:

We have followed your suggestion and made substantial revisions to both the Introduction and the Conclusions, going beyond simply adding two paragraphs.

Overall revision of the Introduction: We have substantially restructured the Introduction to better motivate the need for an integrated framework coupling coordination analysis with time-lag diagnostics. The opening paragraph now emphasizes the co-evolution of SD and LST rather than isolated variables. The third paragraph highlights the snowpack memory effect and the inadequacy of treating SD and LST separately, establishing why a coupled-system view is necessary. The fourth paragraph articulates two fundamental limitations of conventional correlation (conflating interaction strength with system health and ignoring time lags) and poses three progressive scientific questions: system stability under warming, hierarchical controls on coupling strength, and characteristic response time scales across seasons, elevations, and mountain ranges. We then explicitly state that answering these questions requires the combination of the Coupling Coordination Degree Model (CCDM) and time-lagged cross-correlation analysis. A concise paragraph specifies that using long-term high-resolution remote sensing data we quantify coupling degree, coordination level, and response lag patterns, followed by three primary contributions. Finally, a new concluding paragraph explains the diagnostic power of combining coupling coordination with time-lag analysis and details four practical outputs: maps for melt predictability, region-specific parameters for model calibration, elevation-based reference for water planning, and the CD-CCD decoupling as an indicator of vulnerable areas. These revisions ensure readers understand the limitations of conventional methods, the key scientific questions, and how our framework uniquely addresses them.

The fully revised Introduction is provided below. The new concluding paragraph requested by the reviewer appears as the final paragraph of this revised Introduction

Revised Introduction (full text)：

Understanding the interaction between snow depth (SD) and land surface temperature (LST) is critical for predicting hydrological responses and climate feedbacks in snow-dominated regions. As a key interface in land-atmosphere interactions, the seasonal snowpack governs surface energy budgets through its high albedo and low thermal conductivity, while simultaneously modulating water availability via its accumulation and melt (Barnett et al., 2005; Essery, 2013). Within this context, snow depth serves as an integrative state variable that captures the net effect of meteorological forcing and snowpack evolution, and LST provides the primary thermal forcing that drives snowmelt (Lehning et al., 2002a; Marks and Dozier, 1992). Consequently, the co-evolution of SD and LST—rather than either variable in isolation—determines the timing and magnitude of snowmelt runoff, the stability of snow-albedo feedbacks, and the vulnerability of water resources to climate change.

The Xinjiang Uygur Autonomous Region is a hydrologically critical zone in arid Central Asia, encompassing a unique mountain–basin system comprising the Altai, Tianshan, and Kunlun ranges, along with the intervening Junggar and Tarim Basins (Chen et al., 2015). This configuration creates a natural laboratory with pronounced climate, topographic, and snow accumulation gradients (Zhang et al., 2019). The region's water security is fundamentally dependent on snowmelt from these high mountains. However, the mechanistic responses of snowpack dynamics to thermal *forcing—particularly across different mountain ranges and elevation zones—remain poorly quantified at process-relevant scales. The complex interplay between continental climate and extreme topography generates heterogeneous SD-LST interactions that challenge existing models (Li et al., 2020; Wang et al., 2022).*

The SD-LST relationship is inherently complex—exhibiting non-linearities, hysteresis, and strong spatiotemporal heterogeneity (Beniston et al., 2018). Interactions between SD and LST include both immediate thermodynamic adjustments and delayed hydrological feedbacks that vary systematically with elevation, season, and regional climate. For instance, in the Tianshan Mountains, warming has reduced snow duration, delayed accumulation, and accelerated melt (Aizen et al., 2007). The snowpack also possesses a memory effect: the influence of temperature on snow depth persists over time, meaning that the true strength of SD-LST interaction depends on when the thermal forcing occurred; snow can introduce significant lags in thermal responses (Zhang et al., 2021; Li et al., 2016). These elevation-dependent and seasonally variable patterns are widely observed in other mountain ranges as well (Immerzeel et al., 2010; Pepin et al., 2015; Zhang et al., 2013).

The prevailing analytical paradigm that relies on statistical correlations, while robustly establishing empirical relationships, harbors two fundamental limitations (Clark et al., 2011) when applied to snow-climate systems. First, it treats SD and LST as separate variables rather than as an interacting system. Consequently, it cannot distinguish whether the snow-thermal system evolves stably and synergistically or fluctuates erratically under stress. For instance, a strong negative correlation between SD and LST could arise from two fundamentally different situations: a deep, cold snowpack that buffers temperature fluctuations and melts gradually (a well-coordinated, resilient system), versus a thin, vulnerable snowpack that collapses rapidly under warming, with temperature driving snow loss but no buffering capacity remaining (a maladaptive system). Conventional correlation treats these two scenarios identically, thereby masking the critical distinction between coupling intensity and coordination quality. Second, this approach largely overlooks the temporal dimension of snow-temperature interactions. The response of snow to thermal forcing is not *instantaneous; heat propagates through the snowpack at a rate determined by its depth, density, and liquid water content. Conventional correlation-based methods ignore such time lags, and therefore cannot measure how long it takes for temperature changes to affect snow. This propagation delay—ranging from near-zero in shallow ephemeral snow to several weeks in deep, cold snowpacks—is a direct manifestation of snow thermal inertia. Neglecting these time-lags ignores the memory effect inherent to seasonal snowpacks, which is essential for understanding melt timing, energy storage, and the elevational dependence of snow-climate feedbacks.*

Consequently, several fundamental scientific questions remain unanswered. First, under warming pressure, is the SD-LST system maintaining stable and sustainable co-evolution, or has it already shifted toward a maladaptive, unsustainable relationship? Second, what hierarchical control structure, operating from macro-scale climate regimes down to micro-scale local factors, determines the spatial pattern of snow-temperature coupling strength across mountain ranges? Third, what are the characteristic time scales of SD response to thermal forcing, and how do these response lags—ranging from near-instantaneous in shallow ephemeral snow to several weeks in deep, cold snowpacks—vary across seasons, elevations, and mountain ranges? Answering these questions requires an integrated analytical framework that jointly diagnoses coupling strength, coordination quality, and response lags—exactly the combination of the Coupling Coordination Degree Model and time-lagged cross-correlation analysis that this study proposes. The absence of such a framework has long hindered the physical representation of snow processes in land surface and hydrological models (Nijssen et al., 2001).

Using long-term, high-resolution remote sensing data, we apply this framework to systematically investigate SD-LST interactions across Xinjiang and quantify: (1) the degree of coupling; (2) the coordination level across climatic seasons and topographic settings; and (3) the spatiotemporal patterns of response time lags. This investigation makes three primary contributions to cryospheric science: First, it establishes a quantitative, process-informed understanding of how snowpack responds to thermal forcing across one of Central Asia's most hydrologically critical regions. Second, it *introduces and validates an analytical framework—combining coupling, coordination, and lag analysis—that can be applied to other snow-dominated regions globally. Third, it reveals that these interactions are governed by a hierarchical control system—from macro-scale climate regimes down to micro-scale local factors—providing a transferable framework for diagnosing snow-climate vulnerability in other arid mountains.*

Critically, the joint use of coupling coordination and time-lag analysis offers diagnostic power that neither metric alone can achieve. Time lags quantify snowpack thermal inertia, while the CCD reveals whether that inertia reflects a healthy, well-buffered system or a dysfunctional one under stress. Their combination identifies regions where strong temperature forcing is no longer matched by sustainable snowpack evolution—an early warning of emerging vulnerability. Applied across Xinjiang's Mountain-basin systems, this framework delivers practical outputs. Maps of lag times and CCD help pinpoint where snowmelt is regular and predictable versus abrupt and erratic, directly informing forecast lead time adjustments. Region-specific parameters—elevation-dependent CCD thresholds and directional lag changes—provide empirical targets for calibrating snow thermal schemes (e.g., thermal conductivity, albedo decay) in land surface models such as Noah-MP and VIC. The elevation zone where coupling shifts from low to high coordination offers a science-based reference for water resource planning in arid basins. Finally, the decoupling between high CD and low CCD serves as a ready-to-use indicator for targeted monitoring of climatically vulnerable areas. By translating complex snow-climate interactions into measurable, region-specific metrics, this work bridges cryospheric research and operational climate adaptation.

Revision of the Conclusions: We have replaced the original opening paragraph with a concise, forceful paragraph. This paragraph now clearly articulates three unique contributions: distinguishing coupling strength from system state, establishing response lag time as a metric of thermal inertia, and providing a transferable analytical framework for data-scarce, topographically complex regions. The rest of the Conclusions has been condensed to focus on core findings, removing repetitive descriptions and specific numerical values (e.g., exact lag days, years) as also suggested in Comment 3.

New paragraph added at the beginning of the Conclusions (exact wording):

This study delivers three tangible advances for snow-climate science and water management in arid mountains. First, it distinguishes coupling strength from system state, revealing that a strong correlation between SD and LST can mask underlying system dysfunction—a critical insight for identifying vulnerable regions. Second, it establishes response lag time as a physically meaningful metric of snow thermal inertia, enabling regional-scale diagnosis of buffering capacity. Third, it provides a transferable analytical framework that moves beyond conventional correlation to diagnose system stress in data-scarce, topographically complex regions.

We believe that these comprehensive revisions – including the overall reorganization of the Introduction – have made the scientific significance and practical value of our work much more visible and compelling.

Reviewer’s comment 3 (Heading hierarchy and Conclusions length)

“The deepest heading level used in the manuscript is level three, for a journal article this makes the structure appear somewhat fragmented and increases the cognitive load for readers. I recommend simplifying the heading hierarchy to no more than two levels, i.e., only main sections and subsections, without deeper numbering such as 4.2.1 or 4.3.2. Different subtopics within a subsection can be separated by lead-in sentences or bolded phrases without creating additional numbered headings. Furthermore, the Conclusions section is overly long, containing many specific numerical values and repetitive descriptions, which dilutes the key messages. I advise condensing the Conclusions to core findings, each focusing on one essential insight, and moving the remaining detailed information to the Discussion or to supplementary materials.”

Our Response to comment 3:

Headings: We will simplify the heading hierarchy in the final revised manuscript. All third-level headings (e.g., 4.2.1, 4.3.2) will be removed and replaced by bold or italic lead-in phrases within the corresponding subsections. This will improve readability without breaking the logical flow.

Conclusions: As noted above, we have already condensed the Conclusions section from six paragraphs to three, removing specific numerical values and detailed seasonal trend descriptions. The revised Conclusions now focuses only on the essential insights: (1) three tangible advances, (2) the hierarchical control system and the CD-CCD mismatch as an early warning, and (3) the transferability of the framework and future directions. The remaining detailed information (e.g., exact lag times in days, long-term trend slopes) remains in the Results and Discussion sections, as appropriate.

The revised Conclusions (exact wording):

This study delivers three tangible advances for snow-climate science and water management in arid mountains. First, it distinguishes coupling strength from system state, revealing that a strong correlation between SD and LST can mask underlying system dysfunction—a critical insight for identifying vulnerable regions. Second, it establishes response lag time as a physically meaningful metric of snow thermal inertia, enabling regional-scale diagnosis of buffering capacity. Third, it provides a transferable analytical framework that moves beyond conventional correlation to diagnose system stress in data-scarce, topographically complex regions.

We demonstrate that SD-LST interactions are governed by a three-tiered hierarchical control system involving macro-scale climate gradients, meso-scale topography, and micro-scale local factors. Critically, coupling degree and coordination degree are distinct metrics; their spatial mismatch serves as an early warning of system stress, identifying where rapid warming outpaces snowpack adaptive capacity. Response lag time exhibits region-specific signatures, from long, stable lags in deep, cold snowpacks to elevation-threshold-dependent behavior in marginal snow *environments. Long-term trends reveal seasonally differentiated and regionally heterogeneous responses, precluding one-size-fits-all modeling approaches.*

The proposed framework is applicable to other snow-dominated mountain regions facing similar data and topographic challenges. For Xinjiang and analogous arid areas, the identified vulnerability and resilience hotspots provide a scientific basis for prioritizing monitoring and climate adaptation. Future research should integrate process-based snowpack modeling to attribute lag patterns to specific energy balance components, and extend this framework to other Central Asian ranges to advance continental-scale understanding of cryosphere-climate-hydrology interactions under accelerating warming.

Reviewer’s comment 4 (Font size)

“The font size used in the main text is somewhat small, which makes reading somewhat tiring. While the line spacing is not excessively dense, the small font size still impairs readability and the overall reading experience. I suggest that the authors increase the font size appropriately, for example to 11 or 12 points, while maintaining clear line spacing, so as to improve the accessibility and communication efficiency of the paper.”

Our Response to comment 4:

We thank the reviewer for the valuable suggestion. Regarding the font size, the journal’s template specifies a main text font of 10 pt, which we have strictly adhered to in the revised manuscript. To enhance readability within this constraint, we have carefully reformatted the entire paper according to the template, including maintaining a clear 1.5-line spacing and optimizing paragraph and margin settings. We believe these adjustments, together with the legible line spacing, have improved reading comfort. If the journal’s policy permits, we are open to considering a larger font, but we will primarily follow the template requirements. We appreciate the reviewer’s understanding and constructive feedback.

Additional minor corrections

We have also carefully proofread the manuscript and corrected several typographical errors and inconsistencies (e.g., standardising the use of “snow depth (SD)” and “land surface temperature (LST)” throughout). A detailed list of technical corrections is available upon request.

We are grateful again for the reviewer’s thorough and constructive comments. None of the issues raised affect the core scientific conclusions, but addressing them has made the manuscript much clearer, more impactful, and more accessible. We look forward to the next stage of review.

Sincerely,
Haixing Li on behalf of all authors