

Response to Reviewer Comments

Manuscript: egusphere-2025-1198

Introducing a new normalized cryospheric index (NCI) to categorize sub-watersheds on arid environments

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Dear Editor and Reviewer,

We sincerely thank the Reviewer and the Editor for their thorough, constructive, and encouraging evaluation of our revised manuscript. The Reviewer acknowledges that the manuscript has substantially improved and presents valuable data and analyses worthy of publication. We are grateful for the remaining specific suggestions, which we have carefully addressed in this final revision. Below, we provide a detailed point-by-point response to each comment. All changes are highlighted using track changes in the revised manuscript. Reviewer comments are presented in italics, and our responses are in regular text. Specific changes to the manuscript are indicated in blue.

Response to Editor

Please carefully check the reference list and in-text citations, as several references cited in the manuscript appear to be missing from the bibliography. I also recommend incorporating three additional studies into the Discussion section, as they provide relevant context regarding rock glacier dynamics and the hydrological role of debris-covered glaciers in the Andes.

We thank the Editor for this guidance. We have carefully reviewed all in-text citations against the reference list. The reference DGA (2014), cited as the source of GPR ice thickness data for the Del Potro and Tronquitos glaciers, has been added to the reference list. All other citations were verified and found to be present. In addition, the three studies recommended by the Reviewer have been incorporated into the Discussion section and into the Introduction, as detailed in the responses below. A track changes version of the manuscript is provided alongside this response.

Response to Reviewer 1

The Reviewer's overall assessment states:

The authors have substantially improved the manuscript by incorporating all the previous comments. The manuscript presents valuable data and analyses that make an important contribution to the field and, in my view, are worthy of publication.

We sincerely thank the Reviewer for this positive evaluation and for the remaining specific suggestions, which we address in full below.

Comment 1: Missing references in the bibliography

Please carefully check the reference list and in-text citations, as several references cited in the manuscript appear to be missing from the bibliography. For example, DGA (2014), which is referenced as the source of the ice thickness data, should be included in the reference list.

We thank the Reviewer for this careful check. We have reviewed the entire manuscript and confirmed that DGA (2014) was missing from the reference list despite being cited in the text in relation to the GPR-derived ice thickness data for the Del Potro and Tronquitos glaciers used as an independent benchmark in the Discussion (Section 5.1, Table 7). The full reference has now been added to the bibliography:

Dirección General de Aguas (DGA): Estimación de volúmenes de hielo mediante sondeos de radar en zonas Norte, Central y Sur, Informe Final, S.I.T. No. 338, Ministerio de Obras Públicas, Santiago, Chile, available at: <https://bibliotecadigital.ciren.cl/handle/20.500.13082/32675> (last access: 1 June 2025), 2014.

All other in-text citations were cross-checked against the reference list and found to be consistent. The reference list has also been reformatted to conform to The Cryosphere (Copernicus) style and ordered alphabetically.

Comment 2: Incorporation of recommended studies into the Discussion

I also recommend incorporating the following studies into the Discussion section, as they provide relevant context regarding rock glacier dynamics and the hydrological role of debris-covered glaciers in the Andes: Ayala, A., (2025). Less water from glaciers during future megadroughts in the Southern Andes. Commun Earth Environ 6, 860 (2025). Vivero, S., et al. (2021). Combination of aerial, satellite, and UAV photogrammetry for quantifying rock glacier kinematics in the Dry Andes of Chile (30° S) since the 1950s. Frontiers in Remote Sensing, 2, 784015. Burger, F., et al. (2019). Interannual variability in glacier contribution to runoff from a high-elevation Andean catchment: understanding the role of debris cover in glacier hydrology. Hydrological Processes, 33(2), 214–229.

We thank the Reviewer for recommending these highly relevant studies. All three have been incorporated into the revised manuscript — both in the Discussion section, where they are most directly relevant, and in the Introduction, where they strengthen the scientific context for the study. We detail each integration below.

Ayala (2025) — Future megadrought projections

This reference has been integrated at two points in the revised manuscript:

(1) Introduction (Section 1): A sentence has been added to the paragraph discussing the hydrological role of ice-rich permafrost landforms, contextualizing the urgency of the study within projected future water scarcity:

Added text in Section 1: "In addition, future megadrought projections for the Southern Andes suggest that glacier meltwater contributions may decline markedly, underscoring the critical need to understand and protect all cryospheric water reserves, including periglacial landforms (Ayala, 2025)."

(2) Discussion (Section 5.2): The reference is used to reinforce the policy relevance of identifying and protecting cryospheric sub-watersheds with high NCI values, particularly in the context of future water availability:

Added text in Section 5.2: "Notably, recent projections for the Southern Andes indicate that glacier meltwater contributions may decline substantially during future megadrought conditions (Ayala, 2025), reinforcing the urgency of identifying and protecting cryospheric sub-watersheds such as those ranked highest by the NCI."

Vivero et al. (2021) — Rock glacier kinematics in the Dry Andes

This reference has been integrated at three points in the revised manuscript:

(1) Introduction (Section 1): Added to the paragraph on ice-rich permafrost landforms to provide context for the kinematic variability of rock glaciers in the Dry Andes:

Added text in Section 1: "Multi-decadal photogrammetric reconstructions using aerial, satellite, and UAV data have further revealed significant kinematic variability in rock glaciers of the Dry Andes, highlighting their dynamic nature and importance as cryospheric components (Vivero et al., 2021)."

(2) Discussion (Section 5.1): Used in the new paragraph comparing rock glacier surface velocities between the Copiapó watershed and sites further south. Vivero et al. (2021) reported velocities of 0.26 m yr^{-1} during 1956–1978 and up to $1.25\text{--}1.80 \text{ m yr}^{-1}$ during 2014–2019 for the Tapado, Las Tolas, and El Cachito rock glaciers at 30°S . These values are contrasted with the systematically lower velocities (millimetres per year) detected by Sentinel-1 DInSAR in the Copiapó watershed, which is explained by (a) the drier, colder permafrost conditions imposed by proximity to the South American Arid Diagonal (SAAD), and (b) the predominantly cryogenic (rather than glacigenic) origin of rock glaciers in the study area. The reference Monnier and Kinnard (2015) is also used to support the distinction between glacigenic and cryogenic rock glaciers:

Added text in Section 5.1: "The DInSAR-derived surface velocities of rock glaciers in the Copiapó watershed are systematically lower than those reported for rock glaciers at comparable elevations further south in the Dry Andes. Vivero et al. (2021) documented mean surface velocities of 0.26 m yr^{-1} during 1956–1978 and up to $1.25\text{--}1.80 \text{ m yr}^{-1}$ during 2014–2019 for the Tapado, Las Tolas, and El Cachito rock glaciers at 30°S in the Coquimbo Region. In contrast, the rock glaciers of the Copiapó watershed ($26^{\circ}41'\text{--}28^{\circ}24'\text{S}$), as detected by Sentinel-1 DInSAR, exhibit velocities on the order of a few millimetres per year, one to two orders of magnitude slower. Two complementary factors explain this systematic difference. First, the Copiapó watershed lies within or immediately adjacent to the South American Arid Diagonal (SAAD), where extremely limited precipitation results in drier, colder permafrost conditions and reduced ground-ice temperatures relative to sites further south, leading to higher ice viscosity and reduced creep rates (Cicoira et al., 2021; Koenig et al., 2025). Second, the rock glaciers of the Tapado complex are glacigenic landforms connected to glacier ice and push moraines, whereas the rock glaciers inventoried in the Copiapó watershed are predominantly cryogenic in origin, characteristically exhibiting lower ice contents and slower creep rates (Monnier and Kinnard, 2015). The slower kinematics observed are therefore physically consistent with both the arid thermal regime and the cryogenic origin of the rock glaciers in this study."

(3) Section 4.5 (Thickness estimations on periglacial landforms): The reference is used to contextualize the thickness estimates within the broader Dry Andes kinematic literature, alongside Burger et al. (2019) and Ayala (2025):

Added text in Section 4.5: "These thickness estimates are further contextualized by multi-decadal kinematic records from the Dry Andes showing that rock glaciers exhibit marked interannual velocity variability (Vivero et al., 2021), and by debris-covered glacier studies demonstrating that supraglacial debris exerts a strong control on the hydrological behavior of ice bodies in high-elevation Andean catchments (Burger et al., 2019). The long-term

hydrological relevance of these landforms is reinforced by projections indicating reduced glacier meltwater contributions under future megadrought scenarios (Ayala, 2025)."

Burger et al. (2019) — Debris cover and glacier hydrology

This reference has been integrated at two points in the revised manuscript:

(1) Introduction (Section 1): Added to the paragraph discussing the hydrological response of debris-covered glaciers, providing evidence for the interannual variability controlled by supraglacial debris:

Added text in Section 1: "The interannual variability of this meltwater contribution is strongly modulated by debris cover thickness and continuity, which can substantially alter glacier hydrological response across seasons and years (Burger et al., 2019)."

(2) Discussion (Section 5.1): Used in the context of the debris-covered glacier discussion, complementing the comparison between clean-ice and debris-covered glacier dynamics in the Copiapó watershed:

Added text in Section 5.1: "The interannual variability in glacier meltwater contribution in high-elevation Andean catchments is strongly modulated by the insulating effect of supraglacial debris, which attenuates ablation rates and delays the hydrological response of debris-covered glaciers relative to their clean-ice counterparts (Burger et al., 2019)."

Comment 3 (Specific): Line 831 — Thickness estimations on periglacial landforms

831 → *Thickness estimations on periglacial landforms: The change has been accepted*

As detailed in the responses to Comment 2 above, all three recommended references (Ayala, 2025; Vivero et al., 2021; Burger et al., 2019) have been incorporated both at line 831 (Section 4.5, Thickness estimations on periglacial landforms) and in the Introduction (Section 1). The specific text added to Section 4.5 is presented in the response to Comment 2 above (blue text). The additions to the Introduction are also specified above for each reference individually.

These additions ensure that the three references are consistently present in both the scientific context (Introduction) and the analytical discussion (Sections 4.5 and 5.1), as requested.

Summary of all changes implemented in this revision

1. DGA (2014) added to the reference list (previously missing despite being cited in the text).
2. Reference list reformatted to The Cryosphere (Copernicus) style and ordered alphabetically.
3. Ayala (2025) incorporated into Section 1 (Introduction) and Section 5.2 (Discussion) to contextualize future megadrought impacts on glacier water contributions.
4. Vivero et al. (2021) incorporated into Section 1 (Introduction), Section 4.5 (Thickness estimations), and Section 5.1 (Discussion), where it anchors a new paragraph comparing rock glacier surface velocities between the Copiapó watershed and the Tapado site (30°S), explaining the systematic velocity difference through proximity to the SAAD and the cryogenic versus glacial origin of rock glaciers.

5. Burger et al. (2019) incorporated into Section 1 (Introduction), Section 4.5 (Thickness estimations), and Section 5.1 (Discussion), providing context for the role of debris cover in modulating glacier meltwater contributions.

6. Monnier and Kinnard (2015) added to the reference list and cited in Section 5.1 to support the distinction between glacial and cryogenic rock glaciers.

7. The Conclusions section (Section 6) has been substantially revised. Section 6.1 (Main findings) was rewritten to present the key results with greater precision and scientific depth, including quantitative statements on the NCI rankings, ice mass distribution, the empirical snow–discharge link ($R^2 = 0.58$), and the management implications of the dual behaviour identified between ice-rich southern sub-watersheds and snow-driven northern sub-watersheds. The previous Section 6.2 (then titled “Limitations”) has been reorganised into two subsections: the new Section 6.2 (“Relevant topics detected”) highlights three findings with broader implications beyond the Copaó basin, namely the exclusion of gelifluction taluses from Chile’s national periglacial inventory, the unexpectedly large ice thicknesses detected by ERT, and the physical interpretation of the anomalously slow DInSAR velocities. A new Section 6.3 (“Limitations and outlook”) consolidates the remaining limitations and future directions, including the priority of deriving spatially explicit fractional snow cover uncertainties and the policy relevance of protecting high-NCI sub-watersheds in the context of projected megadroughts (Ayala, 2025).

We believe that the revised manuscript now fully addresses all remaining comments from the Reviewer and the Editor. Beyond the specific points raised, we have taken the opportunity to substantially improve the Conclusions section, which now presents the main findings with greater quantitative precision, reorganises the discussion of broader implications and limitations into dedicated subsections, and strengthens the connection between the NCI results and water-resource policy. We hope that the manuscript is now suitable for acceptance and publication in *The Cryosphere*.

Sincerely,

Christopher Ulloa, Ayon García, and Anouk Beniest